Farm Irrigation Systems and System Design Fundamentals

2.1 Introduction

Farm irrigation systems must supply water at rates, in quantities, and at times needed to meet farm irrigation requirements and schedules. They divert water from a water source, convey it to cropped areas of the farm, and distribute it over the area being irrigated. In addition, it is essential that the farm irrigation system facilitate management by providing a means of measuring and controlling flow.

This chapter describes farm irrigation systems and their design. The major steps of the design process and the role of the designer are presented and discussed. Several parameters and procedures for establishing the technical and economic feasibility of alternate system designs are described and demonstrated. After reading and studying this chapter the reader should be able to: describe the functions and types of farm irrigation systems, understand the design process and the role of the designer, estimate the design daily irrigation requirement for a farm, evaluate the uniformity, efficiency, adequacy, and effectiveness of irrigation, and compute the total cost of owning and operating a farm irrigation system.

2.2 Functions of Farm Irrigation Systems

The primary function of farm irrigation systems is to supply crops with irrigation water in the quantities and at the time it is needed. Specific functions include:

1. diverting water from the water source,
2. conveying it to individual fields within the farm,
3. distributing it within each field, and
4. providing a means for measuring and regulating flow.
Other functions of farm irrigation systems include crop and soil cooling, protecting crops from frost damage, delaying fruit and bud development, controlling wind erosion, providing water for seed germination, application of chemicals, and land application of wastes.

### 2.2.1 Crop and Soil Cooling

Sprinkling normally tends to cool the air, soil, and crop. During periods when the potential transpiration rate is especially high (and $\theta_e$ approaches $f_c$), cooling due to sprinkler spray evaporation reduces plant water deficits and associated stomatal closure. Cooling has been found to improve the yield and/or quality of several crops including almonds, apples, beans, cherries, cotton, cranberries, cucumbers, flowers, grapes, potatoes, prunes, strawberries, sugar beets, tomatoes, and walnuts.

### 2.2.2 Frost Protection

Sprinkle irrigation systems have long been used to protect plants from freezing damage during radiation frosts. Radiation frosts occur on clear, calm nights when plants are cooled 0.5° to 2.0°C (1° to 4°F) below the ambient air temperature as they radiate energy to a cold sky. Heat to maintain plant temperatures above lethal levels is obtained from sprinkled water as it cools and freezes on plant surfaces. For low-growing crops in zero wind conditions sprinkling at a rate of 2 to 3 mm/h (about 0.1 in/h) should start before the temperature reaches 0°C (32°F) at the plant level and continue until the plant is free of ice. Higher application rates will be required if wind is present, when air temperatures are low, or for taller growing crops. Strawberries have been protected from temperatures as low as $-6°C (22°F)$. Alfalfa, tomatoes, peppers, cranberries, apples, cherries, and citrus have also been successfully protected.

Fruit trees have been protected from freezing damage with undertree sprinklers that do not wet tree foliage. Since plant protection depends primarily on the convective transfer of heat from the sprinkled water to plant surfaces, undertree sprinkling provides less frost protection than overtree sprinkling. Undertree sprinkling does not, however, have the limb breakage (due to ice accumulation) problem associated with overtree sprinkling.

### 2.2.3 Delaying Fruit and Bud Development

The date of deciduous fruit-tree blossoming can be controlled by sprinkling during the bud growth period in the spring. Cooling of buds resulting from the evaporation of sprinkler spray slows bud growth and delays blossoming. Freezing damage is prevented by sprinkling in a manner that delays blossoming until the danger of frost has past.
2.2.4 Controlling Wind Erosion

Wind erosion of bare soil surfaces that are in a loosened condition because of tillage or freezing can be controlled with irrigation. Wet soils are more resistant to wind erosion. Upon drying, however, sandy soils resume their erodibility, while surface crusting that are largely resistant to wind erosion develop in medium-to-fine-textured soils. Tilling fine sandy loams and other similar textured soils after irrigation produces clods that are erosion resistant until broken down by water or additional tillage. Sandy soils must be kept moist to control wind erosion.

2.2.5 Germinating Seeds

Sprinkling can be used to control the temperature and salt content of seed beds. When soil temperatures are high due to high incoming radiation, sprinkling can reduce soil surface temperatures and prevent “burning off” of young seedlings. Where salts contained in irrigation water accumulate on the surface of furrow irrigated beds, sprinkle irrigation is applied during seed germination to move salts below the seed bed.

2.2.6 Chemical Application

Fertilizers, pesticides, herbicides, desicants, and defoliants are applied with irrigation systems. Some of the advantages of the conjunctive application of chemicals with irrigation water include savings in labor and equipment, better timing, ease of split and multiple controlled application, greater flexibility of farm operations, and enhanced crop production. Only irrigation systems that distribute water uniformly should be used to apply chemicals.

2.2.7 Land Application of Liquid Wastes

Irrigation systems are used to apply liquid wastes from cities, towns, farms, and industrial plants to the land. The wastes, which may contain suspended and/or dissolved materials, are spread over the land where the water is cleaned by filtration as it percolates through the soil. Water treatment prior to land application is necessary when the wastewater contains materials, either organic or inorganic, that are harmful to plants, fungi, bacteria, and other beneficial flora.

2.3 Types of Farm Irrigation Systems

There are several ways of diverting, conveying, and applying irrigation water on farms. The following sections describe alternate types of on-farm diversion, conveyance, and application systems. Facilities for flow measurement and regulation are also discussed.
2.3.1 Diversion Methods

There are two primary ways of diverting surface and ground waters: gravity diversions and pumping plants. When water surface elevations or heads at the water source are sufficient, gravity diversions are used. Otherwise, a pumping plant is utilized to lift and/or provide pressure for conveying and/or applying irrigation water.

2.3.1a Gravity Diversions

The most common type of gravity diversion uses a turnout to admit water from an open water source into farm canals and pipelines. A turnout consists of an inlet, a conduit or other means of conveying water through the bank of the supply canal, and where required, an outlet transition. Turnouts normally include a means of regulating and measuring inflow to the farm such as weirs, sluice gates, or valves. Typical turnouts are diagrammed in Figure 2.1.

On farms that obtain water from pressurized pipelines, a valve is used in lieu of a turnout to admit water into the farm pipeline. A pumping plant is necessary only when the delivery pressure (from the off-farm pipeline) is not sufficient to provide the head needed to operate the farm irrigation system. The inflow rate to the farm is controlled by regulating the delivery pressure and valve opening.

![Diagram of gravity diversions](image)

**Figure 2.1** Some canal turnout structures. (After Skogerboe et al., 1971.) (a) Pipe turnout into a corrugated pipe section without provision for water measurement. (b) Pipe turnout into a concrete pipe with downstream flow measurement and energy dissipation.
2.3.1b Pumping Plants

Pumping plants are used when water must be lifted from the water source and/or when sufficient head (pressure) is not available to operate the farm irrigation system. Pumping plants normally have one or more horizontal or vertical centrifugal pumps powered by either electric motors or internal combustion engines.

(i) Pumps Horizontal centrifugal pumps are normally used with surface sources of water and springs. The pump and power unit can be positioned above the water surface or in a dry pit below the water surface (as in Figure 2.2). Positioning the pump above the water surface facilitates access to the pump for maintenance but makes it necessary to prime the pump (i.e., fill the pump with water) prior to starting the pump. Prime can be maintained when the pump is not operating with foot (check) valves.

Vertical centrifugal pumps similar to the one in Figure 2.3 can be used with either surface (Figure 2.3a) or ground water (Figure 2.3b) sources. Vertical

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**Figure 2.2** Typical mounting positions for horizontal centrifugal pumps.  
(a) Horizontal centrifugal pump located above the water surface.  
(b) Horizontal centrifugal pump located below the water surface (the pump does not require "priming" prior to starting).
Figure 2.3  Typical vertical centrifugal pump installations. (a) Typical vertical centrifugal (turbine) pump installation for pumping surface waters. (b) Typical vertical centrifugal (turbine) pump installation for pumping ground waters.
centrifugal pumps are more difficult to maintain but do not require priming since the pump is submerged. The power unit may be located above the water surface or submerged beneath the pump. Long drive shafts are required when water is being pumped from deep wells and power units are above ground.

(ii) Power Units Electric motors and internal combustion engines are the most common power units for irrigation pumps. Animal- and human-powered pumps are, however, utilized in locations where electricity and fuel are either not available or too expensive. Gasoline, diesel, liquified petroleum gas, and natural gas are the most commonly used fuels for internal combustion engines.

2.3.2 Conveyance Methods

Water is conveyed from the water source to cropped areas of the farm in networks of open channels and/or pipelines. Open channels may be lined or unlined and pipelines partially open to the atmosphere or pressurized.

2.3.2a Open Channels

Open channels are usually graded (have a slope) in the direction of flow and may be either lined or unlined. They are used with all surface and ground water sources and farm application systems. Open channels are lined with hard surface linings such as concrete and asphalt, exposed or covered membranes, and soil sealants to reduce maintenance costs, channel size, and seepage losses through the channel bed and walls. Unlined ditches are used because of their low capital costs and ease of construction and relocation.

2.3.2b Pipelines

On-farm pipe networks are classified as open (low head) or closed (pressurized) depending on whether the system is open to the atmosphere. Both types of pipelines can be laid on the ground surface or buried. Surface pipes have the advantage (over buried pipes) of portability, while buried lines can be placed below the tillage zone where damage by farm machinery, vehicles, vandals, etc., is minimized. When buried above the frost depth, provisions for draining buried pipelines are required.

Pipelines have several advantages over open channels. Well-constructed pipelines eliminate seepage and evaporative losses, avoid weed problems, and are normally safer than open channels (since humans and equipment cannot fall into the water stream). Pipelines also permit the conveyance of water uphill against the normal slope of the land and, unlike open channels, can be installed on nonuniform grades. The use of buried pipe eliminates pad construction for open channels, allows use of the most direct routes from the water source to fields, and minimizes the loss of productive land (since crops can be planted up to or over the pipelines). Portable pipe systems laid on the soil surface can be removed while cultural operations are in progress. Open channels may, however, be more economical than pipelines when land is flat and flows are large.
(i) Open (Low Head) Pipelines  Because low head pipelines are open to the atmosphere, heads in these pipelines seldom exceed 15 m (50 ft). A profile view of a typical low head pipeline is shown in Figure 2.4. The stand pipe provides head regulation, water release, vacuum relief, and air release. Open pipelines are not generally used with application systems that require more than 6 m (20 ft) of head.

(ii) Closed (Pressurized) Pipelines  Pressurized pipelines normally supply application systems that require more than 6 m (20 ft) of head. Pressurized pipelines are not open to the atmosphere and do not contain structures such as standpipes. Pressure regulating, check, air release, and vacuum relief valves are used instead of standpipes and pump stands to provide flow and pressure control as well as to protect the pipeline.

2.3.3 Application Systems

Sprinkle-, trickle-, and surface- (gravity-) type application systems are used to distribute water to crops. Each of these systems and the conditions that favor their use are discussed in the following sections.

![Diagram of low-pressure (open) pipelines with two types of overflow stands.](image)
2.3.3a Sprinkle Systems

Sprinkle irrigation systems similar to the ones in Figure 2.5 use sprinklers operating at pressures ranging from 70 to over 700 kPa (10 to over 100 psi) to form and distribute “rainlike” droplets over the land surface. Sprinkle systems apply water efficiently, have relatively high capital costs and low labor requirements, and use more energy than other application methods. Sprinkle irrigation is adaptable to many soils and terrains. It can be successfully used to irrigate

1. permeable soils that are difficult to irrigate using other application systems,
2. lands with combinations of shallow soils and terrain that prevent proper land smoothing needed for other application systems,
3. land having steep slopes and easily erodible soils, and
4. undulating terrain that would be too costly to smooth for use of other application systems.

Sprinkle systems can be used for frost protection, fertilizer and chemical application, wind erosion control, crop and soil cooling, delaying fruit and bud development, germinating seeds, and land application of wastes.

2.3.3b Trickle Systems

Trickle irrigation is the frequent, slow application of water either directly onto the land surface or into the root zone of the crop. It is based on the fundamental concepts of irrigating only the root zone of the crop (rather than the entire land surface) and maintaining the water content of the root zone at near optimum levels. Trickle irrigation is accomplished using pressures ranging from 15 to 200 kPa (2 to 30 psi) to drip water one-drop-at-a-time onto the land or into the root zone, spray

Figure 2.5 Different types of sprinkle irrigation systems.  
(a) Center pivot. (b) Traveler (soft hose). (c) Hand move.  
(d) Side roll. (e) Solid set.
it as a fine mist over portions of the land surface, or bubble it onto the land surface in small streamlets. Different types of trickle irrigation systems are shown in Figure 2.6.

Conditions that favor the use of trickle irrigation include

1. high-value row crops,
2. a limited, expensive or saline water supply,

Figure 2.6 Different types of trickle irrigation systems. (a) Drip system on grapes. (b) In-line drip emitter. (c) Spray system. (d) Microspray sprinkler.
3. water application must be precise in location and amount to minimize drainage or for precise salinity management, and
4. above ground portions of plants must be dry to control bacteria, fungi, and other pests and diseases.

Waters with high concentrations of particulate, chemical, and/or biological materials that clog trickle system components make trickle irrigation difficult and expensive. Trickle irrigation is adaptable to most soils and terrains.

2.3.3c Surface (Gravity) Irrigation

Most irrigation throughout the world is accomplished via surface (gravity) techniques. Types of surface irrigation systems are shown in Figure 2.7. Surface irrigation systems generally require a smaller initial investment (except when extensive land smoothing is needed), are more labor intensive, and apply water less efficiently than other types of irrigation systems. Surface irrigation systems are best suited to soils with moderate to low infiltration capacities and land with relatively uniform terrain and slopes less than 2 percent.

2.3.4 Flow Measurement and Regulating Methods

Flow data are invaluable in adjusting (regulating) farm irrigation system operation to properly irrigate all parts of the farm and in detecting maintenance problems such as clogged or plugged screens, worn pumps and sprinklers, pipeline and ditch leaks etc. Since flow measurement and regulation are essential prerequisites to effective system management and maintenance, they must be carefully and

![Figure 2.7](image)

Figure 2.7 Different types of surface irrigation systems. (a) Water advancing across a graded border. (b) Level basin with a corner inlet. (c) Basins in an orchard. (d) Siphon tubes delivering water from an unlined head ditch into two furrows.
2.4 Designing Farm Irrigation Systems

Flow measurement in open channels and pipelines is discussed in Chapter 8. Weirs, flumes, and orifice plates are the most commonly used devices to measure flow in open channels. In pipelines, venturi meters, orifices, elbow meters, rotating mechanical flowmeters, ultrasonic devices, and various types of Pitot tubes are used to measure flow. Flow is regulated with checks and check structures, division boxes, and gates in open channels and various types of valves in pipelines.

Flow measuring and regulating devices should be located in the diversion facilities to measure and control system inflow, where flows are divided between and within fields, and at other critical points throughout the system. Drainage water leaving each field can also be measured.

2.4 Designing Farm Irrigation Systems

Farm irrigation systems are designed to match the physical and economic setting in which they are to operate. The physical setting is determined by climate, soils, topography, and the location of buildings, rivers and streams, roads, etc. Such factors as the cost of land, the existence of markets, production costs (for fertilizers, seed, herbicides, etc.), the cost of energy and water for irrigation, the landowner’s personal debt situation, and crop prices establish the economic setting of the farm.

The job of the designer is to match the system to the physical and economic setting in which it is to operate. The primary steps in farm irrigation system design include

1. assembling data needed for design,
2. identifying and evaluating a water source,
3. determining the design daily irrigation requirement (DDIR),
4. designing alternative systems for the farm,
5. evaluating the performance of alternative system designs,
6. determining the annual cost of alternative system designs, and
7. selecting the most suitable system design.

These design steps are described in the following sections.

2.4.1 Data Requirements for Design

An essential part of the design process is quantifying the physical and economic setting of the farm. The success of the project may depend on this important and often time-consuming task. The time and effort spent gathering design data should not be underestimated, since it can exceed the time spent designing the system.

Table 2.1 lists the principal data required to design a farm irrigation system. In the United States many of these data are routinely collected and published.
### Table 2.1 Principal Data Needed for Farm Irrigation System Design

<table>
<thead>
<tr>
<th>Data</th>
<th>Specific Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate</td>
<td>Several years of temperature, relative humidity, wind, or solar radiation data for estimating daily irrigation requirements for each crop (Precise climatic requirements depend on the ET method used)</td>
</tr>
<tr>
<td>Crop</td>
<td>Areal distribution and amount (area) of each crop to be grown; suitability of each crop to climate, soils, farming practices, markets, etc.; Kc values, planting dates, etc., for each crop to be grown over the expected life of the project</td>
</tr>
<tr>
<td>Soils</td>
<td>Areal distribution of soils; water holding and infiltration characteristics, depth, drainage requirements, salinity, erodibility of each soil.</td>
</tr>
<tr>
<td>Water supply (Chapter 3 details water supply data and analysis)</td>
<td>Location of water source; water surface elevation; hydrologic and water quality information for assessing the availability and suitability of the water for irrigation; water right information</td>
</tr>
<tr>
<td>Energy source</td>
<td>Location, availability, and type of source(s); cost information</td>
</tr>
<tr>
<td>Capital and labor</td>
<td>Capital available for system development and availability, level of technical skill, and cost of labor</td>
</tr>
<tr>
<td>Other</td>
<td>Topographic map showing location of roads, buildings, drainways, and other physical features that influence design; financial situation of farmer, farmer preferences.</td>
</tr>
</tbody>
</table>

Climatic data can be obtained from the National Oceanic and Atmospheric Administration (NOAA) for thousands of locations throughout the United States. For some locations all the data needed for Penman-type ET calculations are recorded, while only daily temperature and precipitation data are available for other locations. Soils data are published by the U.S. Department of Agriculture Soil Conservation Service (SCS) for most U.S. locations and are available from the SCS, universities, and libraries. Irrigation requirement information and system design recommendations are also available from the SCS. The U.S. Department of Interior Geological Survey monitors and publishes water supply and quality data for the principal surface and ground water sources of the United States.

Other important sources of data include agricultural scientists such as agricultural engineers, agronomists, horticulturalists, economists, and soil scientists. One of the most important sources of data is field measurements. Legal assistance may also be required to resolve water right conflicts and other legal questions.
2.4.2 Water Source Evaluation

Identifying a reliable water source is a prerequisite to successful irrigation. Irrigation water is obtained from a variety of surface and ground water sources. Surface sources include streams, lakes, and canals, while wells and springs are the principal ground water sources.

A detailed analysis of legal, hydrologic, and water quality factors is required to determine the total volume and volumetric flowrate (volume per unit time) that a water source can reliably supply year after year. The suitability of the water source is determined by comparing these values to the irrigation requirements of the farm. In situations where the expense of obtaining water or its limited availability does not allow full irrigation of the farm, strategies for partially irrigating the farm should be considered. Partial irrigation strategies include restricting the area of the farm that is fully irrigated and/or limiting the depth of water applied (deficit irrigation).

Surface and ground water sources of water are discussed in Chapter 3. Other topics covered in Chapter 3 include the hydrologic, water quality, economic and legal factors that determine the suitability of a water source for irrigation, procedures for determining the total volume and volumetric flowrate that surface and ground waters can reliably supply, and a discussion of water quality and its effect on the suitability of water for irrigation.

2.4.3 Determining the Design Daily Irrigation Requirement

The design daily irrigation requirement (DDIR) is usually the rate at which an irrigation system must supply water to achieve the desired level of irrigation. In some situations, however, the largest daily irrigation requirement is associated with land preparation (like rice paddy formation) and not evapotranspiration (ET). The remainder of this section assumes that DDIR is determined by ET.

DDIR has dimensions of length per unit of time. Typical units for DDIR are inches per day or gallons per minute per acre (gpm/ac) in the English system and millimeters per day or liters per minute per hectare (l/min/ha) in the SI system.

The DDIR for an irrigation system varies with the crops, climate, and soils of the farm. DDIR values are largest for crops that have relatively shallow rooting depths, are sensitive to water stress, and/or use water rapidly. Farms located in climates with high daily ET rates and low precipitation have the largest DDIR. Several years of climatic data are required to quantify year-to-year variations in daily ET and precipitation and to properly evaluate DDIR.

Generally, DDIR’s for crops grown in soils with low water holding capacities, such as sands, are higher than those for crops grown in finer textured soils with higher water holding capacities. This is because the interval between irrigations (i.e., the irrigation interval) increases with water holding capacity and the average daily irrigation requirement is smallest for longer irrigation intervals.
The DDIR value for a farm is determined from several years of daily irrigation requirement (DIR) data. DIR’s for each year of climatic record are usually computed with one of the Penman-type equations or pan evaporation and Eqs. 1.8 and 1.25 with \( E_i = 100 \) percent. DDIR is normally less than the peak DIR, since some of the water needed to meet the peak DIR can normally be obtained from the soil. In situations where no water can be obtained from the soil, DDIR equals the peak DIR.

DDIR is determined using Eq. 2.1.

\[
DDIR = \frac{AD}{\Pi_{\text{min}}}
\]  

(2.1)

where

\( AD = \) allowed depletion of soil water between irrigations (mm, in);

\( \Pi_{\text{min}} = \) minimum irrigation interval during the irrigation season (days).

Although AD normally equals RAW, AD may exceed RAW for deficit irrigation strategies. The use of Eq. 2.1 is illustrated in Example 2.1.

**EXAMPLE 2.1** Determining DDIR When RAW Exceeds the Peak DIR

**Given:**
- daily irrigation requirement data in Figure 2.8
- RAW = 150 mm

**Required:**
DDIR

**Solution:**
from Figure 2.8 \( \Pi_{\text{min}} = 14 \) days

\[
DDIR = \frac{\text{RAW}}{\Pi_{\text{min}}} = \frac{150 \text{ mm}}{14 \text{ days}} = 10.7 \text{ mm/day}
\]

The design daily irrigation requirement for a farm, \( DDIR_f \), is determined by computing the cumulative irrigation requirement for the farm using the procedure illustrated in Example 2.1. The farm’s cumulative irrigation requirement is computed by summing the daily irrigation requirement of the crops grown on the farm. The farm’s daily irrigation requirement is computed with

\[
(DIR_f)_j = \frac{\sum_{i=1}^{n} (A_i)(DIR_i)_j}{\sum_{i=1}^{n} A_i}
\]

(2.2)
Figure 2.8  (a) Daily and (b) cumulative irrigation requirements.

where

\[ DIR_f = \text{daily irrigation requirement for the farm (mm/day, in/day)}; \]
\[ DIR_i = \text{daily irrigation requirement for crop } i \text{ (mm/day, in/day)}; \]
\[ A_i = \text{area of crop } i \text{ (ha, acres)}; \]
\[ n = \text{number of crops grown on farm}; \]
\[ j = \text{day of growing season}. \]
A frequency analysis of several years of DDIR\(_f\) values is required to account for year-to-year fluctuations in climate. Such an analysis allows a probability of occurrence to be assigned to each DDIR\(_f\). For example, a frequency analysis enables the DDIR\(_f\) that will, on the average, be exceeded 10 percent of the time to be determined.

The return period is often used in lieu of the probability of occurrence. The relationship between these terms is given in Eq. 2.3.

\[
RP = \frac{100}{P}
\]  

(2.3)

where

PR = return period (years);
P = probability of occurrence (percent).

Using Eq. 2.3, a 20 percent probability of occurrence is equivalent to a 5-year return period. A 5-year return period DDIR\(_f\) means that the DDIR\(_f\) will be, on the average, exceeded once in 5 years but does not guarantee it. It may be exceeded in each of the 5 years or not at all. A 5-year return period indicates that historically, the DDIR\(_f\) has, on the average, been exceeded once in 5 years.

The first step in a frequency analysis is to compute DDIR\(_f\) values for each of several years. Next, the probability of occurrence of each DDIR\(_f\) is estimated using Eq. 2.4.

\[
P = \left(1 - \frac{R}{M + 1}\right)100
\]  

(2.4)

where

P = probability that a given value will be exceeded in percent;
R = rank of DDIR\(_f\) on a list of DDIR\(_f\) values in ascending order
(R for the smallest DDIR\(_f\) value = 1);
M = number of DDIR\(_f\) values.

A plot of P versus DDIR\(_f\) or an extreme value type I (minimum) probability distribution (Haan, 1977) is used to smooth the data for interpolation. A probability distribution transforms P so that a linear relationship between the transform of P and DDIR\(_f\) results. The Weibull transformation of P is

\[
W = \log\left[\log\left(\frac{P}{100}\right)\right]
\]  

(2.5)

where \(W\) is the Weibull transform of \(P\).

The following example illustrates a frequency analysis of DDIR\(_f\) data using Eqs. 2.4 and 2.5.
EXAMPLE 2.2  A Frequency Analysis to Determine Design Daily Irrigation Requirements for a Farm (DDIRₙ) for Various Return Periods

**Given:**
- 22 years of DDIRₙ values

**Required:**
DDIRₙ values that will be exceeded 50, 20, 10, and 5 percent of the time (i.e., for return periods of 2, 5, 10, and 20 years, respectively).

**Solution:**

*Solution Steps*
1. arrange DDIRₙ data in ascending order,
2. compute P for each DDIRₙ using Eq. 2.4,
3. compute W for each DDIRₙ using Eq. 2.5,
4. plot W versus DDIRₙ,
5. compute W values for P values 50, 20, 10, and 5 percent,
6. read DDIRₙ values from plot for W values corresponding to P values of 50, 20, 10, and 5 percent (2, 5, 10, and 20 year return periods).

The following table summarizes solution steps 1–3.

<table>
<thead>
<tr>
<th>DDIRₙ (mm)</th>
<th>Rank (R)</th>
<th>P</th>
<th>RP (years)</th>
<th>W</th>
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<tbody>
<tr>
<td>7.1</td>
<td>1</td>
<td>95.65</td>
<td>1.04</td>
<td>-1.71</td>
</tr>
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<td>7.4</td>
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<td>9.7</td>
<td>17</td>
<td>26.09</td>
<td>3.83</td>
<td>-0.23</td>
</tr>
<tr>
<td>9.9</td>
<td>18</td>
<td>21.74</td>
<td>4.60</td>
<td>-0.18</td>
</tr>
<tr>
<td>9.9</td>
<td>19</td>
<td>17.39</td>
<td>5.75</td>
<td>-0.12</td>
</tr>
<tr>
<td>10.2</td>
<td>20</td>
<td>13.04</td>
<td>7.67</td>
<td>-0.05</td>
</tr>
<tr>
<td>10.2</td>
<td>21</td>
<td>8.70</td>
<td>11.50</td>
<td>0.03</td>
</tr>
<tr>
<td>10.9</td>
<td>22</td>
<td>4.35</td>
<td>23.00</td>
<td>0.13</td>
</tr>
</tbody>
</table>
### Table 2.2 Design Daily Irrigation Requirement Values at Selected U.S. Locations for Various Crops Grown on Deep, Medium-Textured, Moderately Permeable Soils

<table>
<thead>
<tr>
<th></th>
<th>Washington (Columbia Basin)</th>
<th>California (San Joaquin Valley)</th>
<th>Texas (Southern High Plains)</th>
<th>Arkansas (Mississippi Bottoms)</th>
<th>Nebraska (Eastern Part)</th>
<th>Colorado (Western Part)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm/day</td>
<td>in/day</td>
<td>mm/day</td>
<td>in/day</td>
<td>mm/day</td>
<td>in/day</td>
</tr>
<tr>
<td>Corn</td>
<td>6.9</td>
<td>0.27</td>
<td>6.6</td>
<td>0.26</td>
<td>7.6</td>
<td>0.30</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>6.4</td>
<td>0.25</td>
<td>6.4</td>
<td>0.25</td>
<td>7.6</td>
<td>0.30</td>
</tr>
<tr>
<td>Pasture</td>
<td>7.4</td>
<td>0.29</td>
<td>8.1</td>
<td>0.32</td>
<td>6.4&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.25&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Grain</td>
<td>5.3</td>
<td>0.21</td>
<td>4.3</td>
<td>0.17</td>
<td>3.8</td>
<td>0.15</td>
</tr>
<tr>
<td>Sugar beets</td>
<td>6.6</td>
<td>0.26</td>
<td>5.6</td>
<td>0.22</td>
<td>6.4</td>
<td>0.25</td>
</tr>
<tr>
<td>Cotton</td>
<td>5.6</td>
<td>0.22</td>
<td>6.1</td>
<td>0.24</td>
<td>6.4</td>
<td>0.25</td>
</tr>
<tr>
<td>Potatoes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deciduous</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>orchards</td>
<td>5.3</td>
<td>0.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Citrus orchards</td>
<td>4.8</td>
<td>0.19</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grapes</td>
<td>4.6</td>
<td>0.18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual legumes</td>
<td>4.6</td>
<td>0.18</td>
<td>7.1</td>
<td>0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soybeans</td>
<td>4.8</td>
<td>0.19</td>
<td>5.1&lt;sup&gt;d&lt;/sup&gt;</td>
<td>0.20&lt;sup&gt;d&lt;/sup&gt;</td>
<td>3.0&lt;sup&gt;e&lt;/sup&gt;</td>
<td>0.12&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Shallow truck</td>
<td>4.8</td>
<td>0.19</td>
<td>5.1&lt;sup&gt;d&lt;/sup&gt;</td>
<td>0.20&lt;sup&gt;d&lt;/sup&gt;</td>
<td>3.0&lt;sup&gt;e&lt;/sup&gt;</td>
<td>0.12&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Medium truck</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep truck</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tomatoes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tobacco</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>4.3</td>
<td>0.17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wisconsin (State)</td>
<td></td>
<td>Indiana (State)</td>
<td></td>
<td>Piedmont Plateau</td>
<td></td>
</tr>
<tr>
<td>-------------------------</td>
<td>-------------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td></td>
<td>mm/day</td>
<td>in/day</td>
<td>mm/day</td>
<td>in/day</td>
<td>mm/day</td>
<td>in/day</td>
</tr>
<tr>
<td>Corn</td>
<td>7.6</td>
<td>0.30</td>
<td>7.6</td>
<td>0.30</td>
<td>5.6</td>
<td>0.22</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>7.6</td>
<td>0.30</td>
<td>7.6</td>
<td>0.30</td>
<td>6.4</td>
<td>0.25</td>
</tr>
<tr>
<td>Pasture</td>
<td>5.1</td>
<td>0.20</td>
<td>7.6</td>
<td>0.30</td>
<td>6.4</td>
<td>0.25</td>
</tr>
<tr>
<td>Grain</td>
<td>6.4</td>
<td>0.25</td>
<td></td>
<td></td>
<td>4.1</td>
<td>0.16</td>
</tr>
<tr>
<td>Sugar beets</td>
<td>6.4</td>
<td>0.25</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Cotton</td>
<td></td>
<td></td>
<td>5.3</td>
<td>0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potatoes</td>
<td>5.1</td>
<td>0.20</td>
<td>6.4</td>
<td>0.25</td>
<td>4.6</td>
<td>0.18</td>
</tr>
<tr>
<td>Deciduous orchards</td>
<td></td>
<td></td>
<td>4.6</td>
<td>0.18</td>
<td>6.4</td>
<td>0.25</td>
</tr>
<tr>
<td>Citrus orchards</td>
<td>7.6</td>
<td>0.30</td>
<td>6.4</td>
<td>0.25</td>
<td>5.1</td>
<td>0.20</td>
</tr>
<tr>
<td>Grapes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual legumes</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Soybeans</td>
<td>6.4</td>
<td>0.25</td>
<td>7.6</td>
<td>0.30</td>
<td>5.1</td>
<td>0.20</td>
</tr>
<tr>
<td>Shallow truck</td>
<td>5.1</td>
<td>0.20</td>
<td>5.1</td>
<td>0.20</td>
<td>3.6</td>
<td>0.14</td>
</tr>
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<td>Medium truck</td>
<td>5.1</td>
<td>0.20</td>
<td>5.1</td>
<td>0.20</td>
<td>3.6</td>
<td>0.14</td>
</tr>
<tr>
<td>Deep truck</td>
<td>5.1</td>
<td>0.20</td>
<td>5.1</td>
<td>0.20</td>
<td>4.6</td>
<td>0.18</td>
</tr>
<tr>
<td>Tomatoes</td>
<td>5.1</td>
<td>0.20</td>
<td>5.1</td>
<td>0.20</td>
<td>5.3</td>
<td>0.21</td>
</tr>
<tr>
<td>Tobacco</td>
<td>6.4</td>
<td>0.25</td>
<td>4.6</td>
<td>0.18</td>
<td>4.3</td>
<td>0.17</td>
</tr>
<tr>
<td>Rice</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Source: Adopted from Chapter 1, Section 15 of SCS National Engineering Handbook.*

*a* Parts of Georgia, Alabama, North Carolina, and South Carolina.

*b* Cool-season pasture.

*c* Warm-season pasture.

*d* Summer.

*e* Fall.
Solution step 5:

W for P = 50% = −0.52
P = 20% = −0.16
P = 10% = 0
P = 5% = 0.11

Solution step 6:

DDIR$_f$ for P = 50% (RP = 2 yr) = 9.2 mm/day
P = 20% (RP = 5 yr) = 9.9 mm/day
P = 10% (RP = 10 yr) = 10.2 mm/day
P = 5% (RP = 20 yr) = 10.4 mm/day

DDIR values for various crops and location throughout the United States have been developed and published by the Soil Conservation Service (SCS). Table 2.2 summarizes some of these data. The SCS has also developed an equation for estimating DDIR values from peak monthly evapotranspiration for various values of AD. This equation is

$$ DDIR = (0.034) \frac{ET_m^{1.09}}{AD^{0.09}} $$

(2.6)

where

DDIR = design daily irrigation requirement (mm/day, inches/day)

$ET_m$ = average total evapotranspiration for the peak month (mm, in)

AD = soil water depletion allowed between irrigations (mm, in)
2.4.4 Alternative Designs

Normally, there are several alternative system types and configurations that will satisfactorily irrigate a farm. The designer identifies these alternatives and develops detailed designs for the most feasible systems. Each system should provide flexibility for future expansion or changes in management objectives. Some alternatives may be based on full irrigation, while others may involve deficit irrigation strategies.

Identification of alternative systems begins with the selection of an application method. This choice is influenced by landowner preferences, and the physical and economic setting of the farm. Table 2.3 lists major factors that affect application method selection. In situations where this choice is not obvious, each potentially feasible application method is considered in subsequent steps of the design process.

Next, application and conveyance subsystems are located (i.e., laid out) according to farm geometry and terrain. Several alternative layouts may be possible. After eliminating some alternatives by inspection, detailed designs are developed for the remaining layouts.

The hydraulic design of the system begins with the application system, progresses through the conveyance facilities, and ends with the diversion sub-system. During design, sprinklers, emission devices, or furrow shape, spacing, slope, length, and streamsize selection is followed by the determination of pipeline or canal specifications. Pumping plant components and diversion structure specifications are considered last.

2.4.5 Performance of Farm Irrigation Systems

Farm irrigation systems are designed and operated to supply the individual irrigation requirements of each field on the farm while controlling deep percolation, runoff, evaporation, and operational losses. The performance of a farm irrigation system is determined by the efficiency with which water is diverted, conveyed, and applied, and by the adequacy and uniformity of application in each field on the farm. Each of these performance parameters (efficiency, uniformity, and adequacy) is considered in one of the following sections.

2.4.5a Efficiency

The overall efficiency of a farm irrigation system is defined as the percent of water supplied to the farm that is beneficially used for irrigation on the farm. Overall system efficiency, also known as the irrigation efficiency, is defined mathematically by Eqs. 2.7 and 2.8.

\[ E_t = 100 \left( \frac{1 + L}{S} \right) \]  \hspace{1cm} (2.7)

or

\[ E_t = 100 \left( \frac{S - DP - RO - O}{S} \right) \]  \hspace{1cm} (2.8)
<table>
<thead>
<tr>
<th>Site and Situation Factors</th>
<th>Redesigned Surface Systems</th>
<th>Level Basins</th>
<th>Intermittent Mechanical Move</th>
<th>Continuous Mechanical Move</th>
<th>Solid Set and Permanent</th>
<th>Emitters and Porous Tubes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infiltration rate</td>
<td>Moderate to low</td>
<td>Moderate</td>
<td>All</td>
<td>Medium to high</td>
<td>All</td>
<td>All</td>
</tr>
<tr>
<td>Topography</td>
<td>Moderate slopes</td>
<td>Small slopes</td>
<td>Level to rolling</td>
<td>Level to rolling</td>
<td>All</td>
<td>All</td>
</tr>
<tr>
<td>Crops</td>
<td>All</td>
<td>All</td>
<td>Generally shorter crops</td>
<td>All but trees and vineyards</td>
<td>High value required</td>
<td>High value required</td>
</tr>
<tr>
<td>Water supply</td>
<td>Large streams</td>
<td>Very large streams</td>
<td>Small streams nearly continuous</td>
<td>Salty water may harm plants</td>
<td>Small streams</td>
<td>Small streams, continuous and clean</td>
</tr>
<tr>
<td>Water quality</td>
<td>All but very high salts</td>
<td>All</td>
<td>Salty water may harm plants</td>
<td>Salty water may harm plants</td>
<td>All</td>
<td>All</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Average 60–70%</td>
<td>Average 80%</td>
<td>Average 70–80%</td>
<td>Average 80%</td>
<td>All</td>
<td>All</td>
</tr>
<tr>
<td>Labor requirement</td>
<td>High, training required</td>
<td>Low, some training</td>
<td>Moderate, some training</td>
<td>Low, some training</td>
<td>All</td>
<td>All</td>
</tr>
<tr>
<td>Capital requirement</td>
<td>Low to moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Energy requirement</td>
<td>Low</td>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Low to moderate</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>Management skill</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Machinery operations</td>
<td>Medium to long fields</td>
<td>Short fields</td>
<td>Medium field length, small interference</td>
<td>Some interference circular fields</td>
<td>Some interference</td>
<td>May have considerable interference</td>
</tr>
<tr>
<td>Duration of use</td>
<td>Short to long</td>
<td>Long</td>
<td>Short to medium</td>
<td>Short to medium</td>
<td>Long term</td>
<td>Long term, but durability unknown</td>
</tr>
<tr>
<td>Weather</td>
<td>All</td>
<td>All</td>
<td>Poor in windy conditions</td>
<td>Better in windy conditions than other sprinklers</td>
<td>Windy conditions reduce performance; good for cooling</td>
<td>All</td>
</tr>
<tr>
<td>Chemical application</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Very good</td>
</tr>
</tbody>
</table>

where

\[ E_i = \text{irrigation efficiency (percent)}; \]
\[ I = \text{irrigation requirement}; \]
\[ L = \text{leaching requirement (see Section 3.3.1c)}; \]
\[ S = \text{amount of water supplied to the farm}; \]
\[ DP = \text{total deep percolation on farm}; \]
\[ RO = \text{total runoff from farm}; \]
\[ O = \text{operational losses due to planned and accidental spillage from open channels and pipelines} \]

The following example illustrates the use of Eqs. 2.8 to compute the efficiency of an irrigation.

**EXAMPLE 2.3 Computing the Efficiency of an Individual Irrigation**

**Given:**
- 1900 L/min is diverted onto farm each day (24 h)
- each day 0.6 ha of corn and 1.0 ha of alfalfa are irrigated
- RAW for corn is 8 cm
- RAW for alfalfa is 15 cm
- assume that water is uniformly applied over each field (i.e., that the entire corn field receives 8 cm and the entire alfalfa field receives 15 cm of water)

**Required:**
irrigation efficiency for the farm

**Solution:**
use Eq. 2.7 with \( L = 0 \)

\[ S = (1900 \text{ L/min})\left(\frac{60 \text{ min}}{\text{h}}\right)(24 \text{ h})\left(\frac{\text{m}^3}{10000 \text{ L}}\right) = 2736 \text{ m}^3 \]

\[ I = ((8 \text{ cm})(0.6 \text{ ha}) + (15 \text{ cm})(1.0 \text{ ha}))\left(\frac{1 \text{ m}}{100 \text{ cm}}\right)\left(\frac{10000 \text{ m}^2}{\text{ha}}\right) = 1980 \text{ m}^3 \]

\[ E_i = 100\left(\frac{1980}{2736}\right) = 72.4\% \]

Thus, 72.4 percent of the water supplied to the farm is used beneficially for irrigation and 27.6 percent is lost as deep percolation, runoff, evaporation, and/or spillage. The actual \( E_i \) for the farm will probably not be 72.4 percent, however, since it is unlikely that water application would be perfectly uniform as was assumed in the example. Nonuniform application will affect the amount of losses by increasing deep percolation and runoff in overirrigated areas of each field and reducing these losses in under irrigated areas.
When evaluating the performance of a farm irrigation system it is often useful to examine the efficiency of each system component. This allows components that are not performing well to be identified. The following sections define reservoir storage, conveyance, and application efficiencies. The overall system efficiency is the product of these efficiencies as in Eq. 2.9.

\[
E_i = \left(\frac{E_r}{100}\right) \left(\frac{E_c}{100}\right) \left(\frac{E_a}{100}\right) \times 100
\]

where

- \(E_i\) = irrigation efficiency in percent;
- \(E_r\) = reservoir storage efficiency in percent;
- \(E_c\) = conveyance efficiency in percent;
- \(E_a\) = application efficiency in percent.

(i) Reservoir Storage Efficiency

The efficiency with which water is stored in a reservoir is reduced by evaporation and seepage losses. Equation 2.10 defines reservoir storage efficiency.

\[
E_r = 100 \left(1 - \frac{\mathcal{V}_s + \mathcal{V}_e}{\mathcal{V}_i}\right) = 100 \left(\frac{\mathcal{V}_o + \Delta S}{\mathcal{V}_i}\right)
\]

- \(E_r\) = reservoir storage efficiency in percent;
- \(\mathcal{V}_e\) = evaporation volume from the reservoir;
- \(\mathcal{V}_s\) = seepage volume from the reservoir;
- \(\mathcal{V}_i\) = inflow to the reservoir during a time interval;
- \(\mathcal{V}_o\) = outflow volume from the reservoir during a time interval;
- \(\Delta S\) = change in reservoir storage during the time interval, that is, amount of water needed to maintain the water surface in the reservoir at the level that existed at the beginning of the time interval. (\(\Delta S\) is negative when water must be added to the reservoir, and positive when water must be removed.)

The \(\Delta S\) term is often neglected when long time periods are considered. This term should not, however, be neglected for short time periods.

**EXAMPLE 2.4  Computing Reservoir Storage Efficiency**

**Given:**
3220 l/min are being turned into a reservoir
\(\Delta S = 380 \text{ m}^3\) (water must be removed to restore initial water level in reservoir)

**Required:**
reservoir storage efficiency for a 24 h period during which 2650 l/min are being diverted from the reservoir
2.4 Designing Farm Irrigation Systems

**Solution:**

\[ \forall_i = (3220 \text{ l/min})(24 \text{ h})(60 \text{ min/h}) \left( \frac{1 \text{ m}^3}{1000 \text{ l}} \right) = 4637 \text{ m}^3 \]

\[ \forall_o = (2650 \text{ l/min})(24 \text{ h})(60 \text{ min/h}) \left( \frac{1 \text{ m}^3}{1000 \text{ l}} \right) = 3816 \text{ m}^3 \]

\[ E_r = 100 \left( \frac{3816 + 380}{4637} \right) = 90.5\% \]

**(ii) Conveyance Efficiency** Water conveyance efficiency \( E_c \) is the ratio, in percent, of the amount of water delivered by a canal or pipeline to the amount of water delivered to the conveyance system. Efficiency \( E_c \) is computed using Eq. 2.11.

\[ E_c = 100 \left( \frac{\forall_o}{\forall_i} \right) \tag{2.11} \]

where

\( E_c = \) conveyance efficiency in percent;
\( \forall_o = \) volume of water delivered by conveyance system (i.e., outflow);
\( \forall_i = \) volume of water delivered to the conveyance system (i.e., inflow).

**EXAMPLE 2.5 Computing Conveyance Efficiency**

**Given:**

- 2650 l/min of water is being turned into an unlined canal from the reservoir in Example 2.4
- 96 furrows are required to irrigate a field
- the inflow rate to 26 of the furrows is 19 l/min
- the inflow rate to 70 of furrows is 27 l/min

**Required:**

conveyance efficiency

**Solution:**

\[ E_c = 100 \left( \frac{(26)(19)(t) + (70)(27)(t)}{(2650)(t)} \right) \]

where \( t = \) duration of each irrigation

\[ E_c = 100 \left( \frac{2384}{2650} \right) = 90.0\% \]

**(iii) Application Efficiency** Water application efficiency for an irrigated area \( E_a \) is the ratio, expressed in percent, of the volume of water beneficially used by the crop to the volume of water delivered to the area. Application efficiency can be computed for each field of the farm or for the entire farm. Efficiency \( E_a \) is computed using Eq. 2.12:

\[ E_a = 100 \left( \frac{\forall_{ou}}{\forall_a} \right) = 100 \left( \frac{1 + L}{\forall_a} \right) \tag{2.12} \]
where

\( E_a \) = application efficiency in percent;
\( \forall_{bu} \) = volume of water beneficially used by crop(s) in an area;
\( \forall_a \) = volume of water applied in an area;
\( I \) = irrigation requirement for the area;
\( L \) = leaching requirement for the area.

**EXAMPLE 2.6 Computing Application Efficiency**

**Given:**
- each day 0.6 ha of corn and 1.0 ha of alfalfa are irrigated
- RAW for corn is 8 cm
- RAW for alfalfa is 15 cm
- corn is irrigated with 26 furrows each discharging 19 l/min
- alfalfa is irrigated with 70 furrows each discharging 27 l/min
- neglect leaching (\( L = 0 \))
- assume that water is uniformly applied over each field (see Example 2.3)

**Required:**
Application efficiency for

a. corn
b. alfalfa
c. farm

**Solution:**
a. \( E_a \) for corn

\[ \forall_{bu} = (0.6 \text{ ha})(8 \text{ cm}) \left( \frac{1 \text{ m}}{100 \text{ cm}} \right) \left( \frac{10000 \text{ m}^2}{\text{ ha}} \right) = 480 \text{ m}^3 \]
\[ \forall_a = (26 \text{ furrows})(19 \text{ l/min/furrow})(24 \text{ h})(60 \text{ min/h})(1 \text{ m}^3/1000 \text{ l}) = 711 \text{ m}^3 \]
\[ E_a = 100 \left( \frac{480}{711} \right) = 67.5\% \]

b. \( E_a \) for alfalfa

\[ \forall_{bu} = (1.0 \text{ ha})(15 \text{ cm}) \left( \frac{1 \text{ m}}{100 \text{ cm}} \right) \left( \frac{10000 \text{ m}^3}{\text{ ha}} \right) = 1500 \text{ m}^3 \]
\[ \forall_a = (70 \text{ furrows})(27 \text{ l/min})(24 \text{ h})(\text{ha})(60 \text{ min/h})(1 \text{ m}^3/1000 \text{ l}) = 2722 \text{ m}^3 \]
\[ E_a = 100 \left( \frac{1500}{2722} \right) = 55.1\% \]

c. \( E_a \) for farm

\[ E_a = 100 \left( \frac{480 + 1500}{711 + 2722} \right) = 57.7\% \]
EXAMPLE 2.7 Overall Irrigation Efficiency for the Farm Irrigation System in Examples 2.4, 2.5 and 2.6

Given:
$E_r$, $E_i$ and $E_u$ values from Examples 2.4, 2.5, and 2.6

Required:
$E_i$ for farm

Solution:
Using Eq. 2.9

$$E_i = \left( \frac{90.5}{100} \right) \left( \frac{90.0}{100} \right) \left( \frac{57.7}{100} \right) (100) = 47.0\%$$

Thus, 47.0 percent of the water delivered to the reservoir is beneficially used by the crop.

2.4.5b Application Uniformity

The uniformity of application describes how evenly an application system distributes water over a field. The uniformity of application is evaluated using the Christiansen uniformity coefficient ($C_u$). $C_u$ is computed using the following equation:

$$C_u = 100 \left( 1.00 - \frac{\sum_{i=1}^{n} |d_i|}{\mathcal{V}_T} \right) \quad (2.13a)$$

$$d_i = X_i A_i - \overline{V}_i$$

$$\mathcal{V} = \frac{\mathcal{V}_T}{n}$$

$$\mathcal{V}_T = \sum_{i=1}^{n} (A_i)(X_i)$$

where

$X_i$ = depth/volume caught/infiltrated at observation point $i$;
$A_i$ = field area represented by observation point $i$;
$n$ = number of observation points.

When application is perfectly uniform, $C_u$ equals 100 percent.

When the areas represented by each observation point are equal, Eq. 2.13a becomes:

$$C_u = 100 \left( 1.00 - \frac{\sum |d|}{n \overline{X}} \right) \quad (2.13b)$$

$$d = X_i - \overline{X}$$

where

$n$ = number of observations
$\overline{X}$ = average depth/volume amount caught/infiltrated.
The coefficient $C_u$ for sprinkle systems is often evaluated using a grid of catch cans. The volume caught in each can is divided by the area of the can opening to calculate the depth of catch. When catch cans are not used or when the uniformity of surface application methods is being considered, the amount of infiltration at each observation point is used (rather than cup catch) to compute $C_u$. For trickle systems, the volume of water discharged in a specified interval of time at several emission device locations is used.

When numerous observation points are being utilized to evaluate sprinkle or trickle system uniformity and the distribution pattern is nearly normal, $C_u$ can be estimated using Equation 2.14:

$$C_u = 100 - 80.0 \frac{S}{\bar{X}}$$  \hspace{1cm} (2.14)

where

$S =$ standard deviation of the observations;  
$\bar{X} =$ average depth/volume caught/infiltrated.

Equation 2.14 is not recommended for use with surface systems, since their distribution patterns are seldom normally distributed.

Distribution uniformity (DU) is another index of application uniformity. DU is the ratio, expressed in percent, of the average low-quarter amount caught/infiltrated to the average amount caught/infiltrated. DU is defined by Eq. 2.15.

$$DU = 100 \frac{\bar{X}_{LQ}}{\bar{X}}$$  \hspace{1cm} (2.15)

where

$\bar{X}_{LQ} =$ low-quarter average-depth/volume amount caught/infiltrated;  
$\bar{X} =$ average amount depth/volume caught/infiltrated.

**EXAMPLE 2.8  Computing Application Uniformity**

*Given:*

depths of infiltration in centimeters around a field

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>3.5</td>
<td>3.4</td>
<td>3.7</td>
</tr>
<tr>
<td>3.9</td>
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</tr>
<tr>
<td>2.6</td>
<td>2.8</td>
<td>2.7</td>
<td>3.2</td>
</tr>
<tr>
<td>3.7</td>
<td>3.0</td>
<td>2.8</td>
<td>2.6</td>
</tr>
<tr>
<td>4.0</td>
<td>3.5</td>
<td>3.2</td>
<td>4.3</td>
</tr>
</tbody>
</table>
2.4 Designing Farm Irrigation Systems

**Required:**

a. $C_u$

b. DU

**Solution:**

a. $C_u$

\[
\bar{X} = 3.36 \text{ cm} \\
S = 0.50 \text{ cm} \\
\sum |d| = 7.30 \text{ cm}
\]

$C_u$ using Eq. 2.13

\[
C_u = 100 \left( 1.00 - \frac{7.30}{20(3.36)} \right) = 89.3\%
\]

$C_u$ using Eq. 2.14

\[
C_u = 100 - 80.0 \left( \frac{0.47}{3.36} \right) = 88.8\%
\]

b. DU

lowest 5 of catches: 2.6, 2.6, 2.7, 2.8, 2.8 cm

\[
\bar{X}_{LO} = 2.70
\]

\[DU = 100 \left( \frac{2.70}{3.36} \right) = 80.4\%\]

**2.4.5c Adequacy of Irrigation**

The adequacy of irrigation is the percent of the field receiving sufficient water to maintain the quantity and quality of crop production at a "profitable" level. Since this definition requires crop, soil, and market conditions to be specified, adequacy is normally defined to be the percent of the field (farm) receiving the desired amount of water or more.

The adequacy of irrigation is evaluated using a cumulative frequency distribution like the one in Figure 2.9. This figure shows the percent of the field (farm) receiving a given amount of water or more. The dashed line in the figure is the desired depth of application. The adequacy of irrigation for the field (farm) in Figure 2.9 is 50 percent, since 50 percent of the field receives the desired depth of application or more.

Cumulative frequency distribution patterns like the one in Figure 2.9 are constructed by determining the amount of water caught/infiltrated at locations
around the field (farm) and the percent of the total area represented by each location. The amounts are then arranged in descending order and the percent of the field (farm) receiving each amount or more computed. These values are plotted as in Figure 2.9. Example 2.9 illustrates this procedure for determining the adequacy of irrigation for the field in Example 2.8.

**EXAMPLE 2.9** Determining the Adequacy of Irrigation for the Field in Example 2.8.

*Given:*
- infiltrated depths from Example 2.8
- full irrigation = 3.25 cm

*Required:*
adequacy of irrigation

*Solution:*

*Solution Steps*
1. arrange depths in descending order,
2. compute percent of field represented by each depth,
3. compute cumulative area for each depth,
4. plot cumulative area versus depth,
5. determine adequacy from plot.
Steps 1, 2 and 3 calculations are summarized in the following table and plotted in the graph below.

<table>
<thead>
<tr>
<th>Infiltrated Depth (cm)</th>
<th>Percentage of Field</th>
<th>Cumulative Percentage of Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>4.0</td>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td>4.0</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>3.9</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>3.7</td>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td>3.7</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>3.6</td>
<td>5</td>
<td>35</td>
</tr>
<tr>
<td>3.5</td>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td>3.5</td>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td>3.5</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>3.4</td>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td>3.4</td>
<td>5</td>
<td>60</td>
</tr>
<tr>
<td>3.3</td>
<td>5</td>
<td>65</td>
</tr>
<tr>
<td>3.2</td>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td>3.2</td>
<td>5</td>
<td>75</td>
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<tr>
<td>3.0</td>
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<td>80</td>
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<td>2.8</td>
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<tr>
<td>2.8</td>
<td>5</td>
<td>90</td>
</tr>
<tr>
<td>2.7</td>
<td>5</td>
<td>95</td>
</tr>
<tr>
<td>2.6</td>
<td>5</td>
<td>100</td>
</tr>
</tbody>
</table>

From the graph, adequacy = 67 percent.
When the desired depth of irrigation fills the soil to field capacity, a term called the storage efficiency is often used as an index to adequacy. The term $E_s$ is computed using Eq. 2.16:

$$E_s = 100 \left( \frac{S_{rz}}{S_{fc}} \right)$$  \hspace{1cm} (2.16)

where

$S_{rz}$ = amount of water stored in the root zone during the irrigation;
$S_{fc}$ = amount of water to fill the root zone to field capacity

**EXAMPLE 2.10 Computing the Storage Efficiency of an Irrigation**

**Given:**
- infiltration depths from Example 2.8
- average preirrigation water content for the field is 18 percent by volume
- root zone of crop is 60 cm deep
- field capacity is 25 percent by volume

**Required:**
- storage efficiency

**Solution:**

$S_{rz}$ = average depth infiltrated = 3.36 cm

Compute $S_{fc}$ using Eq. 1.30 with $S_{fc} = IRRI$

$$S_{fc} = 60 \left( \frac{25 - 18}{100} \right) = 4.20 \text{ cm}$$

$$E_s = 100 \left( \frac{3.36}{4.20} \right) = 80.0\%$$

**2.4.5d Effectiveness of Irrigation**

The *effectiveness of irrigation* is a term that qualitatively describes the application efficiency, uniformity, and adequacy of irrigation. The desired effectiveness of irrigation (i.e., the desired combination of efficiency, uniformity, and adequacy) maximizes net farm profit. Irrigations with the highest application efficiencies, uniformities, and adequacies are not always desirable, since they do not always maximize net farm profit. An understanding of the relationship between application efficiency, uniformity, and adequacy is needed to identify irrigation systems and strategies that maximize net farm profit.

**(i) Relation Between Uniformity and Application Efficiency**

The relation between uniformity and application efficiency is demonstrated using Figure 2.10. Curves A and B are the cumulative frequency distributions for application systems A and B, which are designed and managed to fill the soil to field capacity and to have equal adequacies (of 50 percent). The flatter slope and smaller range of infiltrated depths for curve A indicates that system A applies water more uniformly.
The areas $a_1$ and $a_2$ are the amounts of over and under irrigation for system A, respectively, while system B amounts of over and under irrigation are given by areas $a_1 + b_1$ and $a_2 + b_2$, respectively. Since a full irrigation (with either system) brings the soil to field capacity, all overirrigation is lost as deep percolation and/or runoff, (in most situations, runoff does not occur when the ordinate of Figure 2.10 is infiltrated depth). Because these losses are largest for system B, it has the lowest application efficiency. Thus, irrigation system designs and management strategies that improve uniformity can be expected to increase application efficiency when the irrigation fills the soil to field capacity. Improved uniformity will not necessarily increase application efficiency when maximum amounts of catch/infiltration are less than the amount needed to fill the soil to field capacity.

Achieving maximum efficiency does not always maximize net farm profit, since increased initial and operating costs are usually associated with improving system uniformities. The benefits of high application efficiency must therefore be carefully balanced against the higher costs associated with higher uniformities. Maximum net farm profit can be achieved with less than maximum attainable uniformities when water, energy, and fertilizer are plentiful and/or inexpensive or when the amount and quality of irrigation water leaving the farm is not a concern.

(ii) Relation Between Adequacy and Application Efficiency
The relation between adequacy and application efficiency is demonstrated using the cumulative frequency distributions in Figure 2.11. The adequacy was decreased from 52 to 16 percent between curves A and B by reducing the depth applied during an irrigation from 3.0 to 2.5 cm while the uniformity remained constant. The area $a + b$ is the amount of deep percolation and runoff resulting from a full irrigation of 3 cm that fills the soil to field capacity, while area $b$ is the loss associated with the 2.5 cm irrigation. Thus, the reduction in adequacy improved the application efficiency. This will be true as long as there are runoff and deep percolation losses.

![Figure 2.10](cumulative-frequency-distributions-for-two-different-irrigation-systems-with-different-uniformities-of-application)
Improving application efficiency by decreasing the adequacy, however, increases the amount of the field (farm) that is underirrigated and thus, reduces the amount and/or quality of crop produced. Achieving maximum net farm profit in this situation requires balancing the benefits associated with higher efficiency and the losses associated with reduced crop yield and/or quality.

2.4.6 Farm Irrigation System Costs

Another important part of irrigation system design is determining the expected annual cost of owning and operating each feasible alternative design. These data are included in the designer’s report and used by landowners to assess the feasibility of irrigating the farm, for selecting the most suitable irrigation system, and in determining the optimum crop mix for the farm. It is utilized by banks, government agencies, and other sources of capital to evaluate the economic soundness of the project and to develop suitable repayment arrangements.

2.4.6a Ownership Costs

Annual ownership costs are often called fixed costs, since they are generally independent of the level of system use. Fixed costs include annual depreciation and interest costs and yearly expenditures for taxes and insurance.

(i) Depreciation  Depreciation is the decrease in system value due to age and obsolescence. Investments that have an indefinite useful life such as water rights and land are not depreciated. The depreciation of a system component that
has a finite useful life is the difference between the item's initial cost and its salvage value.

The initial cost of an item is best determined from actual price quotations. In many situations, however, initial costs are estimated by adjusting the initial costs of identical or similar components of previously designed systems to the current date. Cost trend data such as published by Engineering News-Record or the U.S. Bureau of Reclamation are especially useful in making these adjustments.

A component's salvage value is its value at the end of its useful life and may be positive, zero, or negative. Salvage values are negative when additional expenditures are required to inactivate the component at the end of its useful life.

Table 2.4 gives the expected useful life of several irrigation system components. Ranges are listed since useful life can vary significantly depending on the level of repair, operation, and maintenance practices, and the length of time the system is used each year. The smaller values apply to small units and normal operation and maintenance practices. The larger values are suggested for vigorously engineered, carefully constructed and installed items that are thoroughly and diligently maintained. The useful life values in Table 2.4 are based on an average 2000 hours of use per year.

(ii) Interest Costs  Interest is the return from productively invested capital. When money is borrowed to finance the initial cost of the irrigation system, interest is the money paid for the use of the borrowed money. For landowner financed systems, interest costs reflect returns that could be earned if the capital expended for the irrigation system were invested elsewhere.

Interest costs depend on the minimum attractive rate of return (i.e., the interest rate) and the total initial cost of the irrigation system. A systems cost includes the initial cost of all depreciable components and items such as water rights and land, that are not depreciated. Depreciable items in addition to those in Table 2.4 include fuel storage facilities (for internal combustion engine driven pumps), buildings for housing or storing pumps and other equipment, farm road and drainage facility construction, etc.

(iii) Computing Annual Depreciation and Interest Costs  Equation 2.18 is used to compute annual depreciation and interest costs for an irrigation system.

\[
ADIC = CRF \sum_{j=1}^{NC} PW_j
\]

\[
CRF = \frac{(i)(1 + i)^{AP}}{(1 + i)^{AP} - 1}
\]

where

- \(ADIC\) = annual depreciation and interest costs;
- \(CRF\) = capital recovery factor;
- \(NC\) = number of system components;
- \(PW_j\) = present worth of component \(j\);
- \(i\) = annual interest rate (decimal);
- \(AP\) = analysis period (years).
<table>
<thead>
<tr>
<th>Component</th>
<th>Depreciation (h)</th>
<th>Period (yr)</th>
<th>Percent*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wells and casings</td>
<td>—</td>
<td>20-30</td>
<td>0.5-1.5</td>
</tr>
<tr>
<td>Pumping plant structure</td>
<td>—</td>
<td>20-40</td>
<td>0.5-1.5</td>
</tr>
<tr>
<td>Pump, vertical turbine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bowls,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Column, etc.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pump, centrifugal</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Power transmission</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gear head</td>
<td>30,000-36,000</td>
<td>3</td>
<td>5-7</td>
</tr>
<tr>
<td>V-belt</td>
<td>6,000</td>
<td>5</td>
<td>5-7</td>
</tr>
<tr>
<td>Flat belt, rubber and fabric</td>
<td>10,000</td>
<td>10</td>
<td>5-7</td>
</tr>
<tr>
<td>Flat belt, leather</td>
<td>20,000</td>
<td>10</td>
<td>5-7</td>
</tr>
<tr>
<td>Prime movers</td>
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<tr>
<td>Electric motor</td>
<td>50,000-70,000</td>
<td>14</td>
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<tr>
<td>Diesel engine</td>
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<td>5-8</td>
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<td>Gasoline engine</td>
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<tr>
<td>Air cooled</td>
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<td>4</td>
<td>6-9</td>
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<tr>
<td>Water cooled</td>
<td>18,000</td>
<td>9</td>
<td>5-8</td>
</tr>
<tr>
<td>Propane engine</td>
<td>28,000</td>
<td>14</td>
<td>4-7</td>
</tr>
<tr>
<td>Open farm ditches (permanent)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Concrete structure</td>
<td>20-40</td>
<td></td>
<td>0.5-1.0</td>
</tr>
<tr>
<td>Pipe, asbestos—cement and PVC buried</td>
<td></td>
<td>40</td>
<td>0.25-0.75</td>
</tr>
<tr>
<td>Pipe, aluminum, gated surface</td>
<td></td>
<td>10-12</td>
<td>1.5-2.5</td>
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<tr>
<td>Pipe, steel, waterworks class, buried</td>
<td></td>
<td>40</td>
<td>0.25-0.50</td>
</tr>
<tr>
<td>Pipe, steel, coated and lines, buried</td>
<td></td>
<td>40</td>
<td>0.25-0.50</td>
</tr>
<tr>
<td>Pipe, steel, coated, buried</td>
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<td>0.50-0.75</td>
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<td>Pipe, steel coated, surface</td>
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<td>10-12</td>
<td>1.5-2.5</td>
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<td>15</td>
<td>1.0-2.0</td>
</tr>
<tr>
<td>Pipe, steel, coated and lined, surface</td>
<td></td>
<td>20-25</td>
<td>1.0-2.0</td>
</tr>
<tr>
<td>Pipe, wood, buried</td>
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<td>20</td>
<td>0.75-1.25</td>
</tr>
<tr>
<td>Pipe, aluminum, sprinkler use, surface</td>
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<td>15</td>
<td>1.5-2.5</td>
</tr>
<tr>
<td>Pipe, reinforced plastic mortar, buried</td>
<td></td>
<td>40</td>
<td>0.25-0.50</td>
</tr>
<tr>
<td>Pipe, plastic, trickle, surface</td>
<td></td>
<td>10</td>
<td>1.5-2.5</td>
</tr>
<tr>
<td>Sprinkler heads</td>
<td></td>
<td>8</td>
<td>5-8</td>
</tr>
<tr>
<td>Trickle emitters</td>
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<tr>
<td>Trickle filters</td>
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<tr>
<td>Landgrazing*</td>
<td>none</td>
<td></td>
<td>1.5-2.5</td>
</tr>
<tr>
<td>Reservoirs*</td>
<td>none</td>
<td></td>
<td>2.0-2.0</td>
</tr>
<tr>
<td>Mechanical move sprinklers</td>
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<td></td>
</tr>
<tr>
<td>Continuously moving sprinklers</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Annual maintenance and costs are expressed as a percentage of the initial cost.

*Various stages of expected life, from 7-50 years have been applied to land grading and reservoir costs. If adequate maintenance is practiced, these items will remain unaffected by depreciation. For economic analysis, interest on the investment will cover the costs involved. Life may be limited for reservoirs if watershed sedimentation will reduce its usefulness. Costs associated with water rights can also be handled by an interest charge.
The analysis period used for economy studies of on-farm irrigation systems is typically 20, 25, or 30 years. For large complex projects, periods of 40, 50, and 100 years are commonly used (Thompson et al., 1980).

*Present worth* (PW) is the amount that must be invested at the beginning of the analysis period to return the equivalent of a component’s initial cost plus interest by the end of the analysis period. When the analysis period equals the component’s useful life, PW is computed using

\[ PW = IC - SV \left( \frac{1 + r}{1 + i} \right)^{AP} \]  \hspace{1cm} (2.18)

where

- PW = present worth of component (dollars);
- IC = initial cost of component (dollars);
- SV = salvage value of component (dollars);
- \( r \) = expected annual rate of cost escalation (decimal);
- AP = analysis period (years).

The second term in Eq. 2.18 is the present worth of the salvage value considering the effect of cost escalation.

When the analysis period is shorter than the components useful life, the component will not be fully depreciated at the end of the analysis period. In this case, the final salvage value (at the end of the analysis period) is the sum of the undepreciated and salvage values. Equation 2.19 is used to compute the final salvage value \( SV_f \):

\[ SV_f = IC - (IC - SV) \frac{AP}{UL} \]  \hspace{1cm} (2.19)

where UL is the useful life of the component in years. Equation 2.19 uses straight line depreciation over the useful life to estimate the undepreciated value at the end of the analysis period. When AP is less than UL, PW is computed using Eq. 2.18, with SV = SV_f.

In situations where AP exceeds UL, the component will need to be replaced one or more times during the analysis period. Equation 2.20 is used in such situations.

\[ PW = IC + (IC - SV) \left[ \sum_{j=1}^{N} \left( \frac{1 + r}{1 + i} \right)^{(j)(UL)} \right] - Z \left( \frac{1 + r}{1 + i} \right)^{AP} \]  \hspace{1cm} (2.20)

- \( N \) = integer portion of \( \frac{AP - 1}{UL} \)
- \( Z = IC - (IC - SV) \left( \frac{AP - (N)(UL)}{UL} \right) \)

The second and third terms are, respectively, the present worth of the component replacement costs and the final salvage value (including any undepreciated value).
Example 2.11 demonstrates the use of Eqs. 2.18, 2.19, and 2.20 to compute annual depreciation and interest costs for a pumping plant.

**EXAMPLE 2.11 Computing Annual Depreciation and Interest Costs.**

*Given:*  
centrifugal pump electric motor, and steel pipeline

The following information.

<table>
<thead>
<tr>
<th>Component</th>
<th>Initial Cost ($)</th>
<th>Salvage Value ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
<td>2,000</td>
<td>200</td>
</tr>
<tr>
<td>Motor</td>
<td>1,000</td>
<td>150</td>
</tr>
<tr>
<td>Pipe</td>
<td>6,500</td>
<td>650</td>
</tr>
</tbody>
</table>

*Required:*  
an annual depreciation and interest costs for an annual interest rate of 10 percent, an annual cost escalation rate of 5 percent, and a 30 year analysis period

*Solution:*  
useful lives (from Table 2.4) for

Centrifugal pump = 20 years  
Electric motor = 30 years  
Steel pipe = 40 years

**Present worth calculations:**

*For Pump*  
(use Eq. 2.20, since AP > UL)

\[ N = \text{integer portion of} \, \frac{30 - 1}{20} = 1 \]

\[ Z = \$2000 - (\$2000 - \$200) \frac{30 - (1)(20)}{20} = \$1100 \]

\[ \text{PW} = \$2000 + (\$2000 - \$200) \left( \frac{1.05}{1.10} \right)^{20} - \$1100 \left( \frac{1.05}{1.10} \right)^{30} = \$2437 \]
For Motor
(use Eq. 2.18, since AP = UL)

\[ PW = 1000 - 150 \left( \frac{1.05}{1.10} \right)^{30} \]

\[ = 963 \]

For Pipe
(use Eqs. 2.18 and 2.19, since AP < UL)

\[ SV_r = 6500 - (6500 - 650) \frac{30}{40} = 2113 \]

\[ PW = 6500 - 2113 \left( \frac{1.05}{1.10} \right)^{30} = 5977 \]

\[ ADIC = \left( \frac{(0.1)(1.10)^{30}}{(1.10)^{30} - 1} \right) (2437 + 963 + 5977) \]

\[ = 995 \]

(iii) Taxes and Insurance
The annual costs of taxes and insurance are normally obtained from the appropriate taxing entity and insurance companies, respectively. The combined cost for taxes and insurance normally range from 1.5 to 2.5 percent of the initial value of the irrigation system.

2.4.6b Operating Costs
Annual operating costs include the cost of water, energy, maintenance and repair, and labor. The cost of professional services for such things as irrigation scheduling and fertilizer recommendations should also be included in annual operating costs. The effect of escalating costs can be included by multiplying estimated annual operating costs for the initial year of operation by the equivalent annual cost factor (EACF). EACF is defined by the following:

\[ EACF = \left( \frac{(1 + r)^{AP} - (1 + i)^{AP}}{(r - i)} \right) \left( \frac{i}{(1 + i)^{AP} - 1} \right) \] (2.21)

(i) Annual Water Costs
In many locations (especially in those served by irrigation districts), irrigators are charged for the water they use. These charges are normally assessed on a volume basis.

(ii) Annual Energy Costs
The annual energy cost includes the cost of all energy used to operate the irrigation system. Energy used for pumping, moving equipment within and between fields, injecting fertilizers and other chemicals into the system, etc., must be considered. Energy costs are estimated by calculating the quantity of energy used annually to irrigate the farm and applying the appropriate prices. Procedures for estimating the energy used for pumping, normally the primary use of energy in irrigation, are presented in Section 4.3.6.
(iii) **Annual Maintenance and Repair Costs**  Maintenance and repair costs depend on the number of hours the irrigation system operates, the operating environment, and the quality of maintenance. In addition, there is substantial variation in the prices paid for parts and supplies, and in the wages paid repair and maintenance personnel. Annual maintenance and repair costs should therefore be based on local data whenever possible. When local data are not available, annual maintenance and repair costs for an irrigation system component can be approximated as a percentage of the components initial cost. Table 2.4 lists ranges of percent of initial costs that can be used to estimate annual maintenance and repair costs for several irrigation system components. The total annual maintenance and repair costs for the system is the sum of the component costs.

(iv) **Annual Labor Costs**  The labor required to operate an irrigation system depends on many factors, including the type of application system, the degree of automation, the crop, the frequency and number of irrigations, and the terrain. Labor requirements are estimated by careful analysis of operations or obtained from actual irrigation with similar conditions and systems.

**EXAMPLE 2.12**  Computing Total Annual Ownership and Operating Costs for a Pumping Plant

*Given:*
- the pumping plant in Example 2.11
- information from Example 2.11
- current energy costs of $0.05/kWh are expected to escalate at a rate of 12 percent per year during the analysis period
- total seasonal energy use is expected to be 17,500 kWh
- neglect water and labor costs

*Required:*
- total annual ownership and operating costs

*Solution:*
- annual depreciation and interest costs (from Example 2.12) $995
- taxes and insurance (2 percent of initial value) $(0.02) ($2000 + $1000 + $6500) $190
- energy costs ($0.05/kWh) (17,500 kWh) (3.80)$3325
- maintenance and repair pump: (6 percent of initial cost) = (0.06) ($2000) $120
  motor: (2 percent of initial cost) = (0.02) ($1000) $20
  pipe: (0.5 percent of initial cost) = (0.005) ($6500) $33
Total annual ownership and operating costs $4683

\[ 1^{\text{EACF}} = \left( \frac{(1 + 0.12)^{30} - (1 + 0.10)^{30}}{(1 + 0.12) - (1 + 0.10)} \right) \left( \frac{0.10}{(1 + 0.10)^{30} - 1} \right) \]

\[ = 3.80 \]

2.4.7 Selecting the Most Suitable System Design

The designer should provide the landowner with specifications and a technical and economic analysis for several alternative systems. Each alternative should be thoroughly explained and discussed with the landowner. The landowner then selects, from the alternative designs prepared by the designer, the one that best satisfies landowner's needs, desires, and financial situation. The landowner may also decide that none of the alternatives is acceptable or that irrigation of the farm is not justifiable.

**Homework Problems**

2.1 Using data from Appendix D determine the design daily irrigation requirement (DDIR) for the following.

a. grass and
b. apples with a cover crop

grown in

a. sand,
b. loam, and
c. clay soil.

Compare the DDIR values using a bar graph. Plot DDIR on the vertical axis and crop and soil on the horizontal axis.

*2.2 Use the following air temperature data for July (the warmest month) of each year to determine

a. the range of DDIR values,
b. the average DDIR value, and
c. the DDIR value that will, on the average, be exceeded only 10 percent of the time

for apples with a cover crop grown in a 180-cm-deep sandy loam soil.

* Indicates that a computer program will facilitate the solution of the problems so marked.
The latitude, average minimum relative humidity, wind speed, and ratio of actual to possible sunshine during the irrigation season are 48°N, 25 percent, 2.5 m/s, and 0.85, respectively.

**2.3** Use the data in Appendix D and the computer program developed for Problem 1.36 to determine DDIR for the following.

a. grass,
b. apples with a cover crop, and
c. corn
grown in a very deep
a. sand,
b. loam, and
c. clay soil.

Compare these DDIR values with those obtained in Problem 2.1.

**2.4** An irrigator plans to deficit irrigate corn. Deficit irrigation will be accomplished by allowing 80 percent (rather than 65 percent) of the available water to be depleted between irrigations. The soil is a 150-cm-deep loam. Use data from Appendix D to determine DDIR for the following.

a. full irrigation, and
b. deficit irrigation.

Compare the values of DDIR for the full irrigation and deficit irrigation strategies. Assume that corn is in growth stage 3 (see Figure 1.7) during July.

**2.5** Use pan evaporation data from Appendix D and \( K_c \) information from Example 1.1 to estimate the DDIR for a farm with 50 ha of pasture, 30 ha of corn, and 45 ha of wheat. The predominant soil on the farm is a 100-cm-deep sandy loam.
2.6 A 0.5-ha portion of a corn field is irrigated once a week with a sprinkle irrigation system for 12 hours. Water is applied at a rate of 1000 l/min. There is no runoff. The readily available water holding capacity of the soil for corn is 10 cm. Determine the overall irrigation efficiency.

2.7 6500 l/min is diverted from a stream to irrigate a 25-ha hay field. It takes a week to irrigate the entire field. The readily available water holding capacity of the soil for hay is 15 cm. Estimate the overall irrigation efficiency.

2.8 During periods of peak water use, water is diverted from an irrigation canal into a storage reservoir at a rate of 0.8 m³/s one day/week (water is distributed to other irrigators along the canal during the remaining days of the week). Water is conveyed from the reservoir to a 50-ha field in a 2000-m long unlined ditch. The field is irrigated continuously during peak water use periods. Determine
a. the reservoir storage efficiency,
b. the conveyance efficiency,
c. the application efficiency, and
d. the overall irrigation efficiency

for the following conditions
• the average daily irrigation requirement during peak water use periods is 10 mm/day
• seepage and evaporation losses in the unlined ditch total 1.0 l/min/m
• total seepage and evaporation losses from the reservoir are 100 l/min.

2.9 In order to evaluate irrigation system performance, an irrigator used a neutron probe to measure the water content of the soil before and after an irrigation. Sampling sites were located in a 100-m-square grid throughout the field. The data in the following table are the average water contents of the top 100 cm of soil in percent by volume. The water content when the soil is at field capacity is 30 percent by volume.

<table>
<thead>
<tr>
<th>soil water contents prior to irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.3 16.1 15.2 13.3 14.8 15.5</td>
</tr>
<tr>
<td>15.2 15.4 13.6 15.8 14.3 15.5</td>
</tr>
<tr>
<td>16.2 14.9 15.4 13.8 14.5 15.0</td>
</tr>
<tr>
<td>12.9 14.2 15.0 16.4 17.1 16.2</td>
</tr>
<tr>
<td>14.9 15.3 14.8 15.9 14.2 15.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>soil water contents after irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.2 29.8 31.5 32.0 31.5 29.8</td>
</tr>
<tr>
<td>30.5 30.4 31.2 31.6 31.8 32.1</td>
</tr>
<tr>
<td>29.4 28.5 31.0 31.2 29.9 30.5</td>
</tr>
<tr>
<td>30.6 31.2 31.5 30.1 29.5 30.8</td>
</tr>
<tr>
<td>31.0 31.4 30.6 29.8 32.5 32.0</td>
</tr>
</tbody>
</table>
Determine:
  a. the uniformity of application,
  b. the distribution uniformity, and
  c. the storage efficiency.

2.10 Determine the adequacy of the irrigation in Problem 2.9 for the following desired depths of irrigation:
   a. 16.0 cm,
   b. 14.0 cm, and
   c. 18.0 cm.

*2.11 Using the cumulative frequency distribution curve from Problem 2.10, estimate the application efficiency for a desired depth of irrigation of 16.0 cm.

2.12 Using the cumulative frequency distribution curve from Problem 2.10, estimate the depth of application that is required to obtain 100 percent adequacy. Estimate the application efficiency for this irrigation. The desired irrigation depth is 16 cm.

2.13 An irrigator is considering purchasing one of the following irrigation systems.

<table>
<thead>
<tr>
<th></th>
<th>System A</th>
<th>System B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial cost</td>
<td>$50,000</td>
<td>$40,000</td>
</tr>
<tr>
<td>Salvage value</td>
<td>$5000</td>
<td>0</td>
</tr>
<tr>
<td>Expected life</td>
<td>15 years</td>
<td>20 years</td>
</tr>
<tr>
<td>Annual energy costs</td>
<td>$2500</td>
<td>$2000</td>
</tr>
<tr>
<td>Annual labor costs</td>
<td>$250</td>
<td>$1000</td>
</tr>
<tr>
<td>Annual taxes and insurance</td>
<td>$1000</td>
<td>$800</td>
</tr>
<tr>
<td>Maintenance and repair</td>
<td>$2500</td>
<td>$2000</td>
</tr>
<tr>
<td>Annual water costs</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

For an annual interest rate of 12.0 percent, determine
  a. annual interest and depreciation costs,
  b. total annual fixed costs,
  c. total annual operating costs, and
  d. total annual ownership and operation costs.

Which system has the lowest total annual costs? Use a 20 year analysis period.

2.14 Determine the total annual ownership and operation costs of system A in Problem 2.13 if the irrigator plans to retire in 10 years.

2.15 Repeat Problem 2.13 using an estimated annual rate of cost escalation of 3.8 percent.
References


