12-6-2021

Irrigation Systems Management

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Eisenhauer, Dean; Martin, Derrel L.; Heeren, Derek M.; and Hoffman, Glenn J., "Irrigation Systems Management" (2021). *Biological Systems Engineering: Papers and Publications*. 780.
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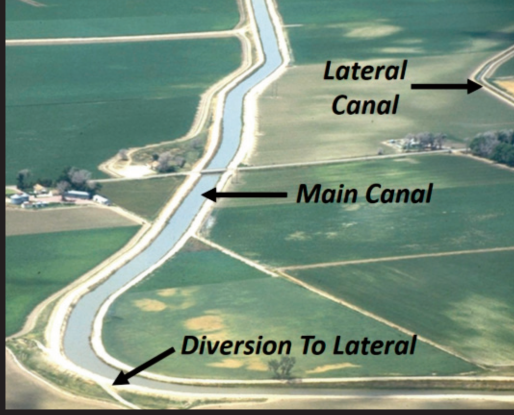

IRRIGATION SYSTEMS MANAGEMENT

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Manufactured in the United States of America
Print date: 6 December 2021

DOI: 10.13031/ISM.2021
International Standard Book Number (ISBN) 978-1-940956-42-8
ASABE Publication 801M0221OA

For more information and material for instructors,
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Copy editing and layout by Peg McCann
Cover design by Melissa Miller
Cover photos:
  Drip lateral, photo courtesy of Toro
  Lake McConaughy, photo courtesy of Steve Melvin, Nebraska Extension
  Weather station, canal, furrow irrigation in corn, and center pivot photos by the authors

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Contents

Foreword xiii

Preface xv

Acknowledgements xvii

About the Authors xix

Common Unit Conversions for Irrigation xxi

Chapter 1 Introduction to Irrigation 1

1.1 Introduction 1
1.2 Role of Irrigation 2
1.3 Irrigation Development 3
1.4 Impact of Irrigation on Water Resources and
 the Environment 6
1.5 Irrigation Management Concepts 7
1.6 Summary 8
Questions 8
References 8

Chapter 2 Soil Water 11

2.1 Introduction 11
2.2 Soil Composition 11
2.3 Soil Water Content 12
2.4 Soil Water Potential 14
2.5 Available Water and the Soil Water Reservoir 16
2.6 Determining Available Water Capacity 18
2.7 Tabulated Values of Typical Soil Properties 19
2.8 Infiltration 20
2.9 Storage of Infiltrated Water 23
2.10 Measuring Soil Water Content and Matric Potential 24
 2.10.1 Gravimetric Method 24
 2.10.2 Feel and Appearance 25
 2.10.3 Neutron Scattering 25

- 2.10.4 Time Domain Reflectometry 26
- 2.10.5 Capacitance Probes 27
- 2.10.6 Tensiometers 27
- 2.10.7 Electrical Resistance Blocks and Granular Matrix Sensors 28
- 2.10.8 Thermal Dissipation Blocks 29
- 2.10.9 Placement of Soil Water Sensors 29
- 2.10.10 Remote Sensing 29

2.11 Summary 30

Questions 30

References 32

Chapter 3 Measuring Water Applications 35

3.1 Introduction 35
- 3.1.1 Need for Water Measurement 35
- 3.1.2 Depth Volume Relationships 35

3.2 Basic Principles of Flow Measurement 37
- 3.2.1 Velocity-Flow-Area Relationship 37
- 3.2.2 Measurement of Mean Velocity 38
- 3.2.3 Distribution of Velocity 38

3.3 Flow Measurement in Pipelines 38
- 3.3.1 Mechanical Meters 38
- 3.3.2 Pressure Differential Methods 40
- 3.3.3 Ultrasonic Measurement 41
- 3.3.4 Magnetic Flowmeters 42

3.4 Flow Measurement in Open Channels 43
- 3.4.1 Velocity Methods 43
- 3.4.2 Pressure Differential Methods 44

3.5 Summary 46

Questions 46

References 47

Chapter 4 Plant Water Use 49

4.1 Introduction 49

4.2 Water Use Processes 50

4.3 Measurement of Evapotranspiration 52
- 4.3.1 Aerodynamic Methods 52
- 4.3.2 Soil Water Methods 53
- 4.3.3 Lysimetry 53
- 4.3.4 Plant Monitoring Methods 55

4.4 Calculating ET 55

4.5 Reference Crop ET 56
4.6 Crop Coefficients... 62
  4.6.1 Basal Crop Coefficients.. 64
  4.6.2 Water Stress Effects.. 68
  4.6.3 Wet Soil Evaporation... 69
  4.6.4 Methods to Describe Canopy Development 71
4.7 Intercropping 71
4.8 Accessing Climatic Information 74
4.9 Summary.. 75
Questions 76
References 77

Chapter 5 Irrigation System Performance 79
5.1 Introduction 79
5.2 Types of Systems 79
  5.2.1 Sprinkler Irrigation 79
  5.2.2 Surface Irrigation 80
  5.2.3 Microirrigation.. 81
5.3 Performance Measures.. 82
  5.3.1 Efficiency... 82
  5.3.2 Application Uniformity 83
  5.3.3 Adequacy of Irrigation.. 86
  5.3.4 Application Efficiency of the Low Quarter: Unification of Efficiency and Uniformity 87
  5.3.5 The Scheduling Coefficient...................................... 90
  5.3.6 Chemical Leaching Losses....................................... 90
  5.3.7 Conveyance Efficiency 92
5.4 System Evaluation 94
5.5 Irrigation System Capacity 95
5.6 Determining System Capacity Requirements................... 95
5.7 Operational Factors 99
5.8 System Characteristics 100
5.9 Safety with Irrigation Systems.................................... 101
5.10 Irrigation Efficiency and Water Resources Sustainability 101
5.11 Summary 103
Questions 103
References 105

Chapter 6 Irrigation Scheduling 107
6.1 Introduction 107
6.2 Plant Response to ET and Soil Water 108
6.3 Capacity of the Soil Water Reservoir 109
    6.3.1 Plant Root Zone 110
6.4 Irrigation Scheduling for Soil Water Maintenance 112
    6.4.1 Checkbook Accounting Method 116
    6.4.2 Simplified Checkbook Method................................. 120
    6.4.3 Soil Water Measurement Method 121
6.5 Scheduling Using Plant Status Indicators....................... 123
    6.5.1 Leaf Water Potential.. 123
    6.5.2 Plant Canopy Temperature.................................... 123
    6.5.3 Other Plant Status Indicators 124
    6.5.4 Stage of Plant Development.................................. 124
6.6 Variable Rate Irrigation Management........................... 125
6.7 Summary.. 126
Questions 126
References 129

Chapter 7 Salinity Management................................... 131
7.1 Introduction 131
7.2 Origin of Salt in Soils 133
7.3 Measurement of Salinity 134
7.4 Crop Salt Tolerance 135
7.5 Sodicity 137
7.6 Toxicity... 138
7.7 Leaching 139
7.8 Reclamation 141
    7.8.1 Saline Soils... 141
    7.8.2 Sodic Soils.. 142
7.9 Salinity and the Environment...................................... 143
7.10 Summary 143
Questions 144
References 144

Chapter 8 Pump and Pipeline Hydraulics 147
8.1 Introduction 147
8.2 Basic Hydraulics.. 147
8.3 Pressure Loss 152
    8.3.1 Introduction.. 152

8.3.2 Pressure Loss Due to Friction Loss 152
8.3.3 Computing Losses Due to Friction 152
8.3.4 Minor Losses Due to Pipeline Fittings....................... 155
8.4 Pipelines 156
8.5 Pumps 158
8.6 Power Requirements... 163
8.7 Energy Consumption 165
8.8 Summary... 169
Questions 169
References 170

Chapter 9 Water Supply Systems................................ 171

9.1 Introduction 171
9.2 Water Rights and Laws 173
9.2.1 Surface Water 173
9.2.2 Groundwater... 173
9.3 Aquifers 174
9.4 Groundwater Supplies 176
9.4.1 Shallow Wells 176
9.4.2 Tube or Cased Wells... 178
9.4.3 Deep Wells and Well Hydraulics 178
9.4.4 Well Construction 179
9.5 Surface Water Supplies... 180
9.5.1 Open Canals 181
9.5.2 Pressurized Delivery Systems................................ 182
9.6 Surface Water-Groundwater Interaction 182
9.7 Reclaimed Water Supplies 183
9.8 Summary... 183
Questions 183
References 184

Chapter 10 Surface Irrigation...................................... 185

10.1 Introduction 185
10.2 Advance, Recession, and Infiltration 187
10.3 Water Balance 190
10.4 Efficiency 191
10.4.1 Calculation of Irrigation Efficiency 191
10.4.2 Improvement of Surface Irrigation Systems 192
10.5 Management of Sloping Furrow Irrigation Systems 193
10.6 Basin and Border Irrigation....................................... 200

10.7 Runoff Recovery 200
  10.7.1 Options for Managing Runoff 200
  10.7.2 Description of Runoff Recovery Systems 201
  10.7.3 Design of Runoff Recovery Systems 201
10.8 Surge Flow Irrigation 203
  10.8.1 The Surge Flow Process 203
  10.8.2 Management of Surge Flow Irrigation 204
10.9 Summary 205
Questions 205
References 207

Chapter 11 Sprinklers 209
11.1 Introduction 209
11.2 System Components 209
11.3 Sprinkler Performance 213
11.4 Lateral Design 220
11.5 Maximum Lateral Inflow 223
11.6 Sprinkler System Design 226
11.7 Frost Protection 228
11.8 Summary 231
Questions 231
References 232

Chapter 12 Moved-Lateral, Gun, and Traveler Sprinkler Systems 233
12.1 Introduction 233
12.2 Periodically Moved Laterals 234
  12.2.1 Types of Systems 235
  12.2.2 Operational Characteristics 238
  12.2.3 Management Plan 242
  12.2.4 Pressure Distribution 246
  12.2.5 Uniformity Issues 250
  12.2.6 Uniformity Evaluation 251
12.3 Solid-Set Systems 254
  12.3.1 System Design 255
  12.3.2 Management Problems 256
12.4 Guns 257
12.5 Travelers 261
  12.5.1 Gun Performance 263
  12.5.2 Field Layout 266

12.5.3 Operational Characteristics 268
12.5.4 Management 270
12.5.5 Other Issues 272
12.6 Summary 273
Questions 274
References 275

Chapter 13 Center Pivots and Lateral Moves 277
13.1 Introduction 277
13.2 Center Pivot Characteristics 279
13.2.1 Sprinkler Discharge 279
13.2.2 Area Irrigated 280
13.2.3 Pressure Distribution 281
13.3 Application Rate 283
13.3.1 Center Pivots 283
13.3.2 Linear or Lateral Move 285
13.4 Sprinkler and Nozzle Selection 285
13.5 Depth of Water Applied 286
13.6 Remote Monitoring of System Operation and Control 293
13.7 Variable Rate Irrigation 293
13.8 Community Shared Center Pivot Systems 294
13.9 Summary 295
Questions 295
References 296

Chapter 14 Microirrigation 297
14.1 Introduction 297
14.2 History and Impact 298
14.3 System Types 298
14.3.1 Surface Drip 299
14.3.2 Microspray 300
14.3.3 Bubblers 300
14.3.4 Subsurface Drip 300
14.4 System Components 301
14.4.1 Control Station 303
14.4.2 Mainline and Manifolds 304
14.4.3 Laterals 305
14.4.4 Water Applicators 307
14.5 Preventing Clogs 308
14.5.1 Filtration 308

14.5.2 Precipitation of Dissolved Solids 311
14.5.3 Organic Materials 311
14.5.4 Flushing and Maintenance 312
14.6 Uniformity 312
14.6.1 Emitter Discharge 312
14.6.2 Discharge Versus Pressure 313
14.6.3 Emission Uniformity 315
14.7 Management 316
14.7.1 Wetted Area 316
14.7.2 Salinity 316
14.7.3 Water Requirements 316
14.8 Summary 317
Questions 318
References 319

Chapter 15 Chemigation 321

15.1 Introduction 321
15.1.1 Advantages of Chemigation 321
15.1.2 Disadvantages of Chemigation 322
15.2 Chemical Injection System 322
15.2.1 Chemical Injection Pumps 322
15.2.2 Tanks and Chemical Injection Tubing 324
15.3 Backflow Prevention and Other Safety Devices 324
15.3.1 Irrigation Pipeline Backflow Prevention Devices 326
15.3.2 Chemical Injection Pipeline Safety Devices 329
15.3.3 Irrigation Pipeline Low Pressure Switch 330
15.3.4 Other Safety Items and Considerations 330
15.3.5 Federal, State, and Local Regulations 330
15.4 Management of Chemigation Systems 331
15.4.1 Injection Rates and Calibration of Injection Devices ... 331
15.4.2 Flushing the Injection and Irrigation System 333
15.5 Summary 336
Questions 337
References 337

Glossary 339

Index 343

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.

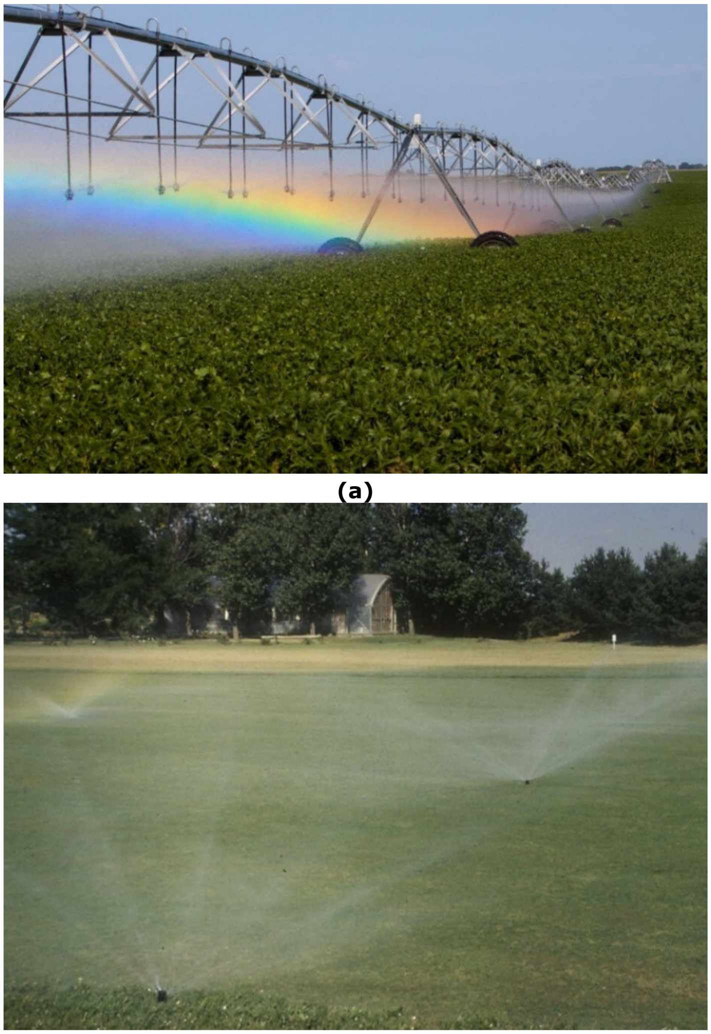
5.2.1 Sprinkler Irrigation

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 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, Nebraska Extension.)

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 courtesy of 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

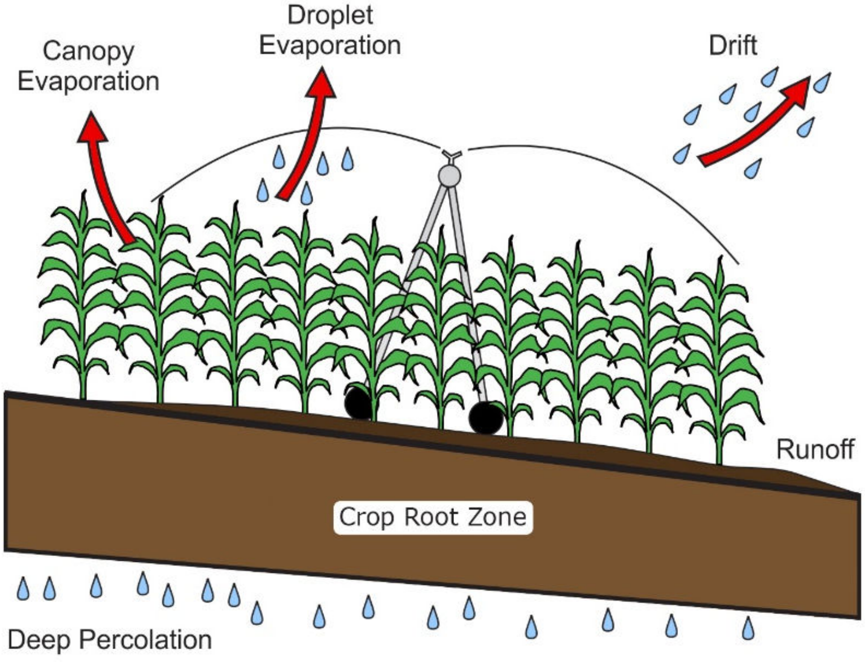


Figure 5.4. Illustration of how water is "lost" from an irrigation system.

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

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

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:

$$DU = \frac{d_{LQ}}{d_z} \qquad (5.2)$$

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, (b) center pivot with end gun providing a larger application depth than the rest of the system, (c) furrow irrigation, and (d) underground sprinkler system for turfgrass. (Photos a and b courtesy of Gary Zoubek, Nebraska Extension; photo c courtesy of Richard Ferguson, Nebraska Extension.)

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:

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

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: $DU = \frac{d_{LQ}}{d_z}$ $\quad DU = \frac{1.5}{2.0} = 0.75$ (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:

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

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

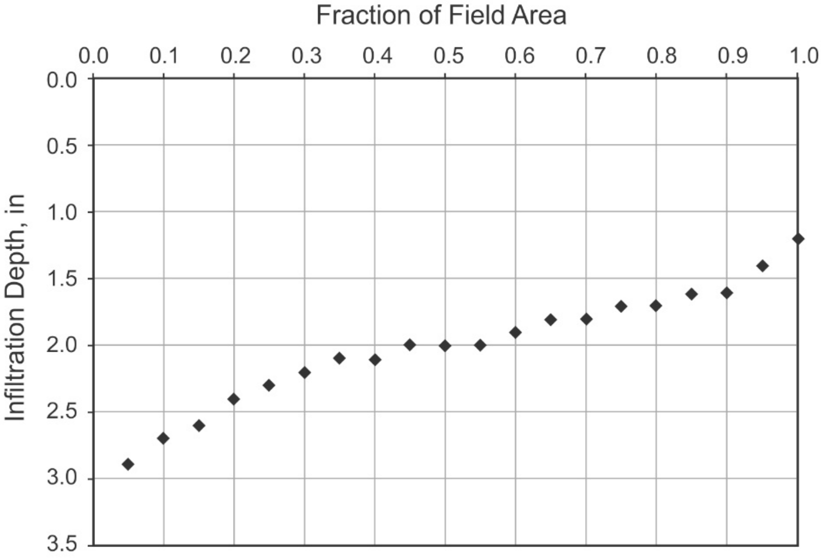


Figure 5.6. Distribution of infiltration based on data from Example 5.1.

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:

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

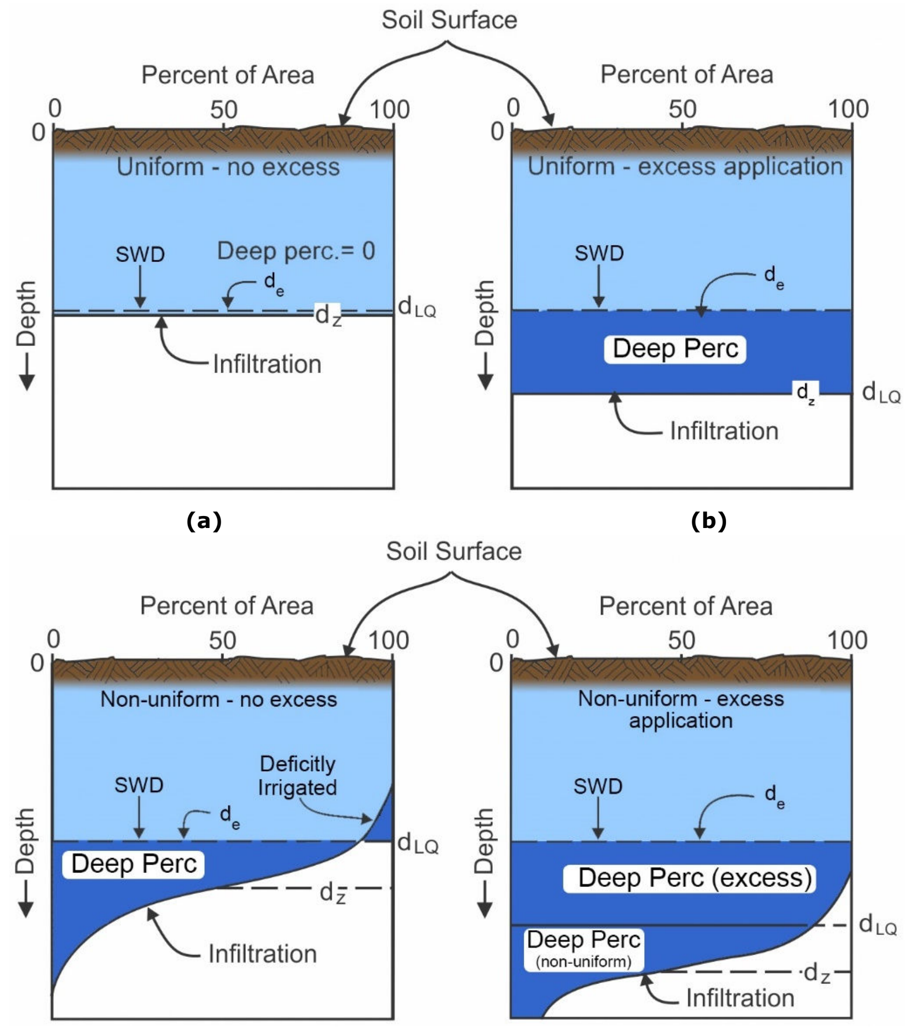
Note that Equation 5.7 accounts for above-ground losses, but the d_z includes both water that will be stored in the root zone and deep percolation. Rearranging Equation 5.2 yields:

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

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:

$$\text{If } d_{LQ} \le SWD\text{, then } d_e = d_{LQ} \tag{5.9}$$

$$\text{If } d_{LQ} > SWD\text{, then } d_e = SWD \tag{5.10}$$

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:

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

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

$$d_{ev} = d_g - d_z - d_r \tag{Eq. 5.6}$$

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

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

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

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

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

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

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

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%

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

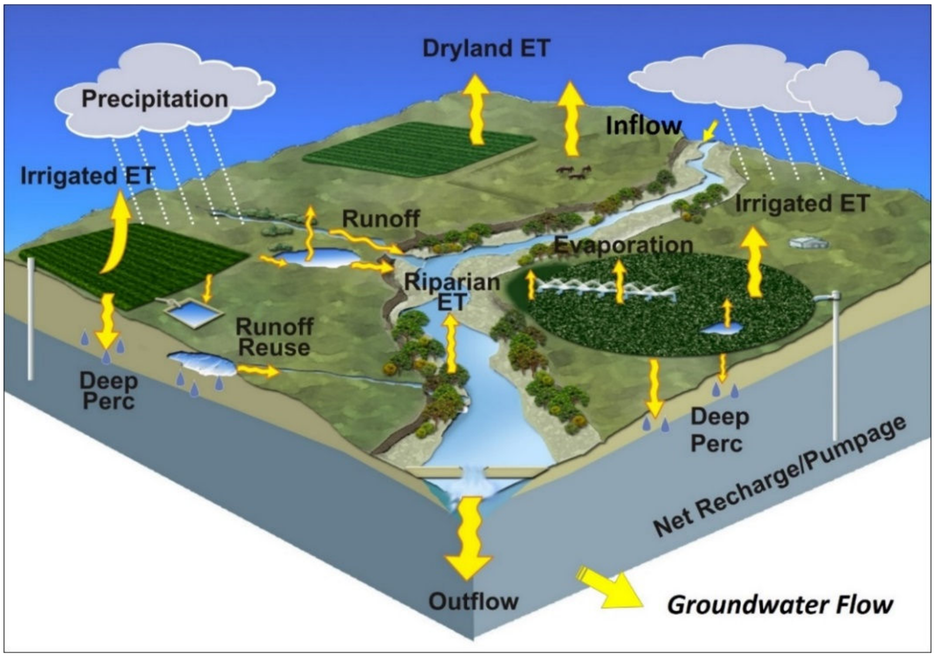


Figure 5.13. Watershed-scale water balance.

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 and d_z exceeds SWD, (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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