ASCE Manuals and Reports on Engineering Practice No. 70

Evaporation, Evapotranspiration, and Irrigation Water Requirements

Second Edition



Task Committee on
Revision of Manual 70

EDITED BY
Marvin E. Jensen, Ph.D., NAE
Richard G. Allen, Ph.D., P.E.

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Sponsored by the
Committee on Evapotranspiration in Irrigation
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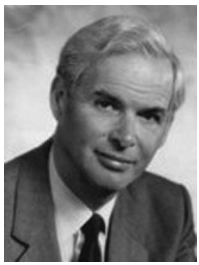
DEDICATION



In loving memory of Doris Jensen, 1929–2009, lifelong spouse, supporter, encourager, and traveling companion of Marvin Jensen.



In fond memory of William Oregon Pruitt, 1922–2009, Irrigation Engineer at the University of California-Davis, who was a primary leader in developing and advancing the concept of reference crop evapotranspiration (ET) and transferable crop coefficients, in trusting the use of energy balance equations to estimate ET, in advocating data and research quality and integrity, and in promoting education in experimental methods. Bill Pruitt, along with Dr. James L. Wright of the USDA-ARS (retired), Kimberly, Idaho, mentored many present-day practitioners on the physics of ET estimation and the requirements for accurate ET measurement. Pruitt and Wright were both longtime members of and contributors to the ASCE Technical Committee on Evapotranspiration in Irrigation and Hydrology.



In fond memory of John Lennox Monteith, 1929–2012, who influenced many Americans in the application of physical principles to describe how plants interact with their immediate environment and microclimate, with his own work leading to the evolution of the Penman combination equation into the Penman-Monteith equation, which has become a primary basis for estimating irrigation water requirements.

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PREFACE

This Manual of Practice provides information on evaporation and evapotranspiration that practicing engineers, hydrologists, and others need to evaluate data received from various sources. It also provides background information to enable practicing engineers, educators, and researchers to improve procedures for estimating evapotranspiration (ET) to achieve the accuracy needed for specific purposes.

This manual updates and expands the scope of the first edition, *Evapotranspiration and Irrigation Water Requirements*, published in 1990. The manual is intended for use by consulting engineers working on water issues and instructors in agricultural and civil engineering, environmental sciences, and agronomy. It is intended to serve as a primary reference for agricultural, environmental, and engineering students, and professionals in water-related agencies. This revised edition incorporates many years of user experience with the previous manual and recent advances in the physics of evaporation from plant and soil surfaces. It also incorporates extensive material from the ASCE *Hydrology Handbook* (1996). The first edition of this manual required many years of planning, and its organization evolved through a series of revisions starting with the report "Consumptive Use and Irrigation Water Requirements" (Jensen 1973). Manual 70 followed the same organization as Jensen (1973), with several new sections added. This revised edition has been restructured based on the experience gained by users of Manual 70. The scope now includes a chapter on evaporation from water surfaces and expanded and more detailed information on estimating evaporation from land surfaces using the crop coefficient method. The manual includes chapters on applying the direct Penman-Monteith and other resistance-based ET estimating methods, producing regional ET and stream depletion estimates, and irrigation requirement estimates. Appendixes A-L have been expanded to include more details on the crop coefficient method, weather data integrity, and derivation of the Penman-Monteith equation and to

include a section summarizing estimating methods not commonly used in the United States.

Data sets used for evaluations have been revised based on new data and information from test sites. In this edition, evaluations focused on accuracy of estimates rather than on comparing various estimating methods, as was done in the first edition. Some comparative statistics among ET methods from the first edition are repeated in Appendix L of this edition.

International System of Units (SI) units are used throughout the manual, as in the first edition. The SI unit used for daily total energy, megajoules per square meter (MJ/m^2), was retained even though some users may prefer to work with average daily or hourly energy units of watts per square meter (W/m^2).

Background information on consumptive use in Chapter 1 of the first edition was originally prepared by early experts such as H. F. Blaney Sr. Part of this information was retained in the second edition for historical purposes. The editors, Jensen and Allen, updated chapters from the first edition and functioned as the principal authors of new chapters and sections. Drafts of updated and new chapters were reviewed by the Task Committee, and the final manuscript was reviewed and accepted by the Blue Ribbon Review Committee.

Marvin E. Jensen
Richard G. Allen

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- Department of Biological Systems Engineering, University of Nebraska, Lincoln, NE;
- Ivan's Engineering, Inc., Centennial, CO;
- Dr. Frank H. Quinn, Great Lakes Environmental Research Laboratory, NOAA, Ann Arbor, MI; Dr. Richard Allen, University of Idaho; and Prof. Emeritus William O. Pruitt, University of California, Davis, CA, were primary contributors to Chapter 4, "Evaporation and Evapotranspiration" of the ASCE *Hydrology Handbook* (1996 2nd Ed.), which served as a major source of material for evaporation from open water used in this revised version of Manual 70;
- The meticulous and long-term collection of accurate and representative agricultural ET data from weighing lysimeter systems by W. O. Pruitt of the University of California, Davis, and Dr. James L. Wright of the USDA-ARS, Kimberly, ID (ret.), contributed substantially to the foundation of crop coefficient tables summarized in this edition; lysimeter measurement of grass reference ET by Pruitt and alfalfa reference ET by Wright provided much of the basis for the form and calibration of the ASCE standardized Penman-Monteith equation;
- The ASCE-EWRI Task Committee on Standardized Calculation of Reference Evapotranspiration Calculation (ASCE 2005) recommended

definitions and calculation procedures for reference ET and supporting equations;
- United Nations Food and Agriculture Organization and the International Commission on Irrigation and Drainage (ICID) supported development of international standardization of ET and associated crop coefficients and helped organize data and methods for ET estimation in FAO-24 (Doorenbos and Pruitt 1977) and FAO-56 (Allen et al. 1998); crop coefficient material from these publications is included in Appendixes B-F;
- Blue Ribbon Panel Reviewers Thomas W. Ley, Colorado Division of Water Resources, Pueblo; Ronald L. Elliott, University of Oklahoma, Stillwater (retired); Thomas Trout, ARS, USDA, Fort Collins, CO (ret.); and Paul W. Brown, University of Arizona, Tucson, contributed substantially to the completeness and accuracy of the manuscript;
- Professor Luis Santos-Pereira and students of the University of Lisbon, Portugal, provided long-term review, testing, and validation of many concepts and methodologies described in this manual;
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- Thanks are due to the Northern Colorado Water Conservancy District for hosting the task committee and providing facilities for the task committee to meet in November 2004; and
- Co-editor Marvin Jensen, who has retired and donated his books, greatly appreciates the tremendous input to the revised manual provided by Rick Allen; Rick has kept abreast of recent developments on measurement and methods for measuring and estimating ET.

NOTATION

Abbreviations, symbols, and common subscripts and superscripts are listed, along with a chart of units used in the International System. Only the most frequently used symbols are included with their common units. Less frequently used symbols and empirical expressions are defined in the text. Some abbreviations and symbols have other dimensions, which are specified in the text. In a few cases, the same symbol is used for different variables; the use will be specified in the text. Symbols for empirical equations are defined in the text.

Abbreviations

AW	Available soil water
BREB	Bowen ratio energy balance
CU	Consumptive use
E	Evaporation
ET	Evapotranspiration
FWS	Free-water surface
LAI	Leaf-area index
MAD	Management allowed depletion
PM	Penman-Monteith
RAW	Readily available water
TAW	Total available water
VPD	Vapor pressure deficit
YTD	Year to date

Symbols

Symbol	Definition	Common units
A	Area	m^2
C_d	Denominator coefficient for the ASCE Standardized PM equation	—
C_n	Numerator coefficient for the ASCE Standardized PM equation	—
E	Evaporation, depth rate	$mm\ d^{-1}$, $mm\ h^{-1}$
E_{eq}	Equilibrium evaporation	$mm\ d^{-1}$, $mm\ h^{-1}$
E_o	Evaporation rate from free water	$mm\ d^{-1}$, $mm\ h^{-1}$
	as latent heat flux density, λE	$MJ\ m^{-2}\ d^{-1}$, $MJ\ m^{-2}\ h^{-1}$, $W\ m^{-2}$
E_{pan}	Evaporation rate from Class A pan	$mm\ d^{-1}$
EC_e	Electrical conductivity of the saturated soil extract ($1\ mmho\ cm^{-1}=1\ dS\ m^{-1}$)	$dS\ m^{-1}$
ET	Evapotranspiration rate	$mm\ d^{-1}$, $mm\ h^{-1}$
ET_c	ET from a particular crop	$mm\ d^{-1}$, $mm\ h^{-1}$
ET_o	ET from a well-watered grass reference crop	$mm\ d^{-1}$, $mm\ h^{-1}$
	as latent heat flux density, λET_o	$MJ\ m^{-2}\ d^{-1}$, $MJ\ m^{-2}\ h^{-1}$, $W\ m^{-2}$
ET_r	ET from a well-watered alfalfa reference crop	$mm\ d^{-1}$, $mm\ h^{-1}$
	as latent heat flux density, λET_r	$MJ\ m^{-2}\ d^{-1}$, $MJ\ m^{-2}\ h^{-1}$, $W\ m^{-2}$
ET_{ref}	Reference evapotranspiration, general	$mm\ d^{-1}$, $mm\ h^{-1}$
G	Heat flux density to the ground	$MJ\ m^{-2}\ d^{-1}$, $MJ\ m^{-2}\ h^{-1}$, $W\ m^{-2}$
G_{sc}	Solar constant	$MJ\ m^{-2}\ h^{-1}$, $W\ m^{-2}$
H	Heat flux density to the air	$MJ\ m^{-2}\ d^{-1}$, $MJ\ m^{-2}\ h^{-1}$, $W\ m^{-2}$
J	Day of the year	
K_A	Clearness index for solar radiation	

(Continued)

Symbol	Definition	Common units
K_B	Clearness index for direct beam solar radiation	
K_c	Crop coefficient general (not the same as the Blaney-Criddle K)	
K_{cb}	Crop coefficient (basal), soil water not limiting transpiration, but the soil surface is visually dry	
K_{cm}	Mean, or single, crop coefficient	
K_e	Coefficient to adjust for increased evaporation from the soil	
K_L	Landscape coefficient	
K_s	Adjustment coefficient for water stress	
K_t	Turbidity coefficient	
LAI	Leaf-area index	
LF	Leaching fraction	
LR	Leaching requirement	
P	Atmospheric pressure	kPa
P	Precipitation	mm
Q_i	Inflow rate	$m^3\ d^{-1}$
Q_o	Outflow rate	$m^3\ d^{-1}$
R	Universal gas constant	$kJ\ kg^{-1}\ K^{-1}$
R	Radiation, general	$MJ\ m^{-2}\ d^{-1}$, $MJ\ m^{-2}\ h^{-1}$, $W\ m^{-2}$
R_a	Exoatmospheric (extraterrestrial) solar radiation on a horizontal surface	$MJ\ m^{-2}\ d^{-1}$, $MJ\ m^{-2}\ h^{-1}$, $W\ m^{-2}$
R_b	Net outgoing long-wave radiation	$MJ\ m^{-2}\ d^{-1}$, $MJ\ m^{-2}\ h^{-1}$, $W\ m^{-2}$
R_{bo}	Net outgoing long-wave radiation on a cloudless day	$MJ\ m^{-2}\ d^{-1}$, $MJ\ m^{-2}\ h^{-1}$, $W\ m^{-2}$
R_n	Net incoming radiation	$MJ\ m^{-2}\ d^{-1}$, $MJ\ m^{-2}\ h^{-1}$, $W\ m^{-2}$
R_{nl}	Net outgoing long-wave radiation	$MJ\ m^{-2}\ d^{-1}$, $MJ\ m^{-2}\ h^{-1}$, $W\ m^{-2}$

(Continued)

(Continued)

Symbol	Definition	Common units
R_{ns}	Net solar radiation	MJ m^{-2} d^{-1}, MJ m^{-2} h^{-1}, W m^{-2}
R_s	Solar radiation at the surface on a horizontal plane	MJ m^{-2} d^{-1}, MJ m^{-2} h^{-1}, W m^{-2}
R_{so}	Solar radiation on a cloudless day	MJ m^{-2} d^{-1}, MJ m^{-2} h^{-1}, W m^{-2}
RH	Relative humidity	%
RH_{max}	Daily maximum relative humidity	%
RH_{min}	Daily minimum relative humidity	%
T	Temperature	°C, K, °F
T_d	Dew point temperature of the air	°C, K
T_{max}	Maximum daily air temperature	°C, K
T_{min}	Minimum daily temperature	°C, K
T_o	Surface temperature	°C, K
T_w	Wet bulb temperature of the air	°C, K
VPD	Vapor pressure deficit	kPa
W_f	Wind function, linear $W_f = a_w + b_w u_2$	
Z	Elevation	cm, m
a, b	Constants	See usage
c_p	Specific heat at constant pressure	kJ kg^{-1} °C^{-1}
d	Zero plane displacement of wind profile	cm, m
e	Water vapor pressure in air	kPa
e_a	Actual vapor pressure	kPa
e_d^o	Saturation vapor pressure at dew point temperature of air	kPa
e_s	Saturation vapor pressure	kPa
e_w^o	Saturation vapor pressure at wet bulb temperature	kPa
e_z^o	Saturation vapor pressure of air at height z	kPa
g	Acceleration of gravity	m s^{-2}
g_s	Surface conductance	m s^{-1}
h	Height of vegetation	cm, m
k	von Kármán's constant	

(Continued)

Symbol	Definition	Common units
k_p	Evaporation pan coefficient	
m	Mass, m_v for water vapor, m_a for dry air, m_s for soil	$kg\ m^{-3}$
q	Specific humidity = $m_v(m_v + m_a)^{-1}$	—
r_a	Diffusion resistance of air layer (aerodynamic resistance)	$s\ m^{-1}$
	r_{ah} for sensible heat flux	$s\ m^{-1}$
	r_{av} for vapor flux	$s\ m^{-1}$
r_i	Internal leaf diffusion resistance	$s\ m^{-1}$
r_l	Single leaf stomatal resistance	$s\ m^{-1}$
r_s	Surface resistance (generally a bulk canopy resistance)	$s\ m^{-1}$
t	Time	s, h, d
u_z	Horizontal wind speed at height z	$m\ s^{-1}$, $km\ d^{-1}$
z_{om}	Roughness length, momentum	cm, m
z_{ov}	Roughness length, heat and water vapor	cm, m
α	Shortwave reflectance coefficient or albedo	
ß	Bowen ratio, $=H/\lambda E$	
Γ	Adiabatic lapse rate	$°C\ m^{-1}$ and $K\ m^{-1}$
γ	Psychrometric constant, $\gamma = c_p P/(0.622\lambda)$	$kPa\ °C^{-1}$
$\gamma*$	Psychrometric constant modified by the ratio of surface resistance to atmospheric resistance, $\gamma^* = \gamma(1 + r_s/r_a)$	$kPa\ °C^{-1}$
Δ	Slope of the saturation vapor pressure-temperature curve, de/dT	$kPa\ °C^{-1}$
Δ	Difference	See usage
ε	Emissivity, ε' = net emissivity, ε_a = atmospheric emissivity, and ε_{vs} = vegetative and soil emissivity	

(Continued)

(Continued)

Symbol	Definition	Common units
λE	Latent heat flux density	MJ m^{-2} d^{-1}, MJ m^{-2} h^{-1}, W m^{-2}
Θ	Volumetric soil water content	
λ	Latent heat of vaporization	MJ kg^{-1}
π	Pi, π=3.14159	
ρ_a	Air density, ρ_w for water vapor, ρ_b for bulk soil, and ρ_y for absolute humidity	kg m^{-3}
σ	Stefan-Boltzmann constant	kJ m^{-2} s^{-1} K^{-4}, MJ m^{-2} d^{-1} K^{-4}, W m^{-2} K^{-4}
ω_s	Sunset hour angle	radians

Subscripts

a	Property of air
o	Property at the atmosphere-surface interface, or reference value
s	Property of soil or the surface
v	Property of vegetation or vapor
w	Property of water
z	Property at height *z*
1, 2	Reference times

Superscript

o	Saturation

International System (SI) of Units

Quantity	Unit	Symbol	Formula
Base Units			
Length	meter	m	
Mass	kilogram	kg	
Time	second	s	
Electric current	ampere	A	

(Continued)

Quantity	Unit	Symbol	Formula
Thermodynamic temperature	kelvin	K	
Amount of substance	mole	mol	
Derived Units			
Force	newton	N	$kg\,m\,s^{-2}$
Pressure	pascal	Pa	$N\,m^{-2}$
energy, work, quantity of heat	joule	J	N m
Radiant flux	watt	W	$J\,s^{-1}$
Electric potential	volt	V	$W\,A^{-1}$
Conductance	siemens	S	$A\,V^{-1}$
Additional Units			
Time	minute	min	1 min = 60 s
	hour	h	1 h = 60 min = 3,600 s
	day	d	1 d = 24 h = 86,400 s
Temperature	degree Celsius	°C	°C = K − 273.15
Volume	liter	L	$1\,L=1\,dm^3=10^{-3}\,m^3$
Mass	metric ton	t	$1\,t=10^3\,kg$

Prefixes

Multiplication factor	Prefix	Symbol
$1{,}000{,}000{,}000=10^9$	giga	G
$1{,}000{,}000=10^6$	mega	M
$1{,}000=10^3$	kilo	K
$0.1=10^{-1}$	deci	D
$0.01=10^{-2}$	centi	C
$0.001=10^{-3}$	milli	m
$0.000001=10^{-6}$	micro	:
$0.000000001=10^{-9}$	nano	H

Sources: ASTM 380-76 (1976); Wandmacher and Johnson (1995).

PART 1
BASIC CONCEPTS

CHAPTER 1
INTRODUCTION AND HISTORY

1.1 INTRODUCTION TO SECOND EDITION

In 1990, the American Society of Civil Engineers (ASCE) published the first edition of *Manuals and Reports on Engineering Practice No. 70*, which was prepared by the Irrigation Water Requirements Committee of the Irrigation and Drainage Division. In 1995, the Committee was renamed the "Evapotranspiration in Irrigation and Hydrology Technical Committee" to include evapotranspiration on nonirrigated lands. The mission of the committee is to advance the science and practice of measuring and estimating evapotranspiration with emphasis on developing and evaluating procedures and tools for integrated water management needed in planning, design, and management of irrigation projects, hydrologic units, and water resources systems. In 2000, when the stock of printed copies had been sold, the Committee appointed a Task Committee to prepare an updated revised edition of the manual.

Since its publication, *Manual 70* has served as a valuable reference for specialists working in agrometeorology, hydrology, and irrigation planning and management. The first edition contained equations for estimating evapotranspiration, both theoretical and empirical, and equations to calculate parameters in the ET equations and for various components of the energy balance. Because the general knowledge base of users has improved greatly over the past two decades, the manual has been restructured for greater ease in applying new technology and standardized calculations, and new information has been included. The manual's current focus is on state-of-the-art technology with less emphasis on older empirical equations and comparisons among various methods of estimating evapotranspiration (ET).

This revised edition includes extensive material from the ASCE *Hydrology Handbook* (Allen et al. 1996), which was a product of the previously noted ET technical committee. Additional material on the standardization of reference ET calculation and clarification of its application developed by a task committee of the ET committee from 1999 through 2004 (ASCE 2005) has been brought into this edition. Because integrated water management often involves estimating evaporation from water bodies such as storage and regulating reservoirs, new material on estimating evaporation (E) from water surfaces has been added.

The revised edition presents various methods for estimating ET and example calculations as a guide to users in applying the new technology. Graduate students preparing to enter one of these fields should find this manual to be useful as a source of basic information. Tables of basic air and water properties, conversion factors, and meteorological tables are retained for reference purposes.

Objectives

Objectives of the first edition were

1. To define and interpret ET, or consumptive use, terminology;
2. To provide practicing engineers, hydrologists, educators, and researchers with a concise summary of factors controlling ET;
3. To describe modern methods for measuring and estimating ET;
4. To describe the major factors to consider in determining irrigation water requirements for fields, farms, projects, and river basins;
5. To summarize representative measured ET from irrigated crops;
6. To evaluate the accuracy of various estimating procedures under various climatic regimes;
7. To present improvements in methods for estimating ET; and
8. To present a selected bibliography for additional information.

The large volume of recent literature on ET makes it impractical for the engineer who does not specialize in this field to review and evaluate available ET data and methodology best suited for solving a particular hydrology, irrigation, or water supply problem. The first edition of this manual was intended to meet this continuing need. Many of these objectives are still current; however, recent improvements and acceptance of standardized methods for estimating ET make review of historic, or empirical, methods less relevant. The new objectives include more focus on the latest technology for estimating ET and E during the growing and the nongrowing seasons and E from water bodies that may be associated with irrigation projects. These technologies include numerical models and the use of remotely sensed variables for estimating ET over large areas.

Chapter Content

This chapter briefly summarizes the history of activities leading to the development of the first edition and preparation of the revised edition. As competition for available water resources continues to increase, transfers of water rights and associated litigation require background on historical water use measurements and the methods previously used to estimate crop water requirements. Summaries of older ET-estimating procedures have been retained in the appendixes for reference purposes along with a summary of comparisons of estimating methods that were presented in the first edition.

Chapter 2 summarizes evaporation (E) and evapotranspiration (ET) processes and controlling factors such as water and energy budgets and vegetation, soil, and management factors. Concepts for estimating evaporation from soils and water surfaces and estimating ET are summarized in Chapter 2 and presented in detail in Chapters 4–6. E and ET measurement methods from land surfaces, including measuring changes in soil water content over time, lysimetry, Bowen ratio energy balance, eddy covariance, and water balance, are introduced in Chapter 2 and discussed in detail in Chapters 7–11.

Chapter 3 describes the soil-plant-atmosphere system beginning with a summary of the physical properties of water, water vapor, and air. Equations relating the various variables are presented. Soil properties are summarized along with equations relating the energy state of soil water. Equations describing the soil water characteristics along with basic equations of water flow through soil are presented. A summary of soil-plant characteristics follows a summary of soil water properties as influenced by soil texture. Vegetative, or crop, properties and plant root characteristics are described.

Chapter 4 presents the surface energy balance with descriptions of the components of net radiation. The chapter also summarizes surface properties affecting the absorption and reflection of solar radiation and presents equations presented for calculating components of net radiation. The surface energy balance is emphasized throughout the revised edition because of its importance in establishing upper limits on the transformation of liquid water to vapor and consequently ET. The surface energy balance forms the basis of the most complete and accurate ET equations, including the Penman and Penman-Monteith methods.

Chapter 5 describes surface-atmosphere interactions that affect net radiation and the ET process. The chapter emphasizes the use of a standardized surface to isolate the evaporative demand due to weather effects. Two surfaces are described. These are a short crop such as clipped grass and a tall crop such as alfalfa having about 0.5-m plant height.

Chapter 6 describes typical methods of estimating evaporation from water surfaces. These include use of an evaporation pan with appropriate

coefficients, water balance, and aerodynamic and energy balance procedures along with the use of combination methods. The chapter presents several examples of estimating evaporation using a combination method and important precautions.

Chapter 7 describes methods of estimating ET from land surfaces using various methods. These methods include a detailed discussion of volumetric measurement of soil water depletion and the use of lysimeters and evaporimeters. Procedures based on energy balance and aerodynamic methods are described, including the Bowen ratio energy balance and eddy covariance methods along with fetch requirements for these methods. The chapter describes the methods in detail along with example calculations and recommendations for collection of accurate data.

Chapter 8 describes the procedures for estimating ET from land surfaces using the Penman-Monteith (PM) equation together with guidelines for characterizing the surface parameters that determine the bulk aerodynamic resistance. The chapter emphasizes the development of the standardized equation for estimating ET from a reference crop surface and the use of vegetative coefficients to estimate ET.

Chapter 9 describes the development of typical soil water profiles during evaporation from soils, stage 1 and stage 2 evaporation, evaporation models for estimating evaporation and evaporation-transpiration relations, and example estimates of evaporation compared with measured evaporation.

Chapter 10 describes the crop coefficient (and landscape coefficient) method for estimating evaporation from land surfaces. It summarizes the development of coefficients to characterize ET as a function of the amount of natural or landscape vegetation or the development of annual or perennial crops. These coefficients are used in conjunction with an estimate of evaporative demand or reference ET such as short-clipped grass or 0.5-m tall alfalfa. An example of generalized mean crop coefficient illustrates the effects of increasing leaf area and surface wetness and decreasing available soil water. The chapter describes basal crop coefficients, representing conditions when the soil surface is visually dry. With basal coefficients, adjustments are made when the surface is wetted by rainfall or irrigation. The chapter also describes characteristics of evaporation from bare soils along with typical soil water profiles in the upper layers of soil. The effects of leaf area on the rate of evaporation are explained along with several methods for estimating the amount of evaporation. Finally, the chapter presents the typical linear Food and Agriculture Organication (FAO)-style crop coefficient curve along with procedures for estimating the magnitude of the various growth stages and durations including several example calculations.

Chapter 11 describes procedures for estimating evaporation from land surfaces using the direct Penman-Monteith (PM) equation and full energy balance equations. Procedures include estimating surface roughness, zero

plane displacement, relationships between surface roughness and plant height, example roughness length scalars, determination of roughness and zero plane displacement from wind profile measurements, leaf area estimates and leaf resistances, bulk surface resistance for various types of green vegetation cover, and stomatal conductance. The chapter also presents procedures for estimating evaporation from soil using the direct PM method and evaporation from intercepted rainfall. Required weather measurements for using the direct PM are described along with procedures for adjusting noncharacteristic data. The chapter presents several calculation examples, including estimates for sloping lands.

Chapter 12 covers several methods for regional estimates of evaporation from land surfaces. These include the complementary approach and the use of energy balance models for forests and grasslands and for cultivated lands. The chapter briefly describes approximating monthly streamflow for ungauged watersheds and data sources for cultivated areas and natural vegetation.

Chapter 13 summarizes the factors to consider in selecting a method for estimating ET, including the available timeframe, required accuracy, and the screening of input climate data. The various methods available for ET calculations are presented.

Chapter 14 summarizes methodology for estimating irrigation water requirements and refers to various chapters and sections in the manual for specific details. It includes procedures for estimating soil leaching requirements, miscellaneous water requirements, and effective precipitation. The chapter also provides brief descriptions of storage and distribution system losses and methods to account for nonuniform water applications.

The appendixes include several appendixes from the first edition such as a saturation vapor pressure-temperature table, conversion factors, thermodynamic constants, air density equations, and an updated glossary. New appendixes include several sets of crop coefficients, a listing of recent publications that include crop coefficients, weather data assessment, contribution of capillary flow to E and ET, a summary of estimating methods no longer commonly used in the United States, a derivation of the Penman-Monteith equation, and a summary of comparisons of estimating methods that were presented in the first edition.

1.2 DEVELOPMENT OF ET AND CU STUDIES IN THE UNITED STATES

Consumptive Use and Evapotranspiration

Consumptive use (CU) of water, or evapotranspiration, is one of the most basic components of the hydrologic cycle. It affects the water