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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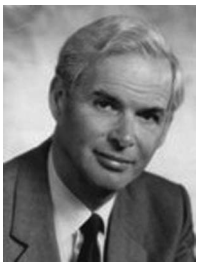
DEDICATION

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.

CONTENTS

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 Land, Air and Water Resources, University of California, Davis, CA;
- 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;
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- Professor Ayse Kilic and students of the University of Nebraska-Lincoln, provided substantial review, testing, and validation of concepts and calculation methodologies;
- 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	$MJ\ m^{-2}\ d^{-1}$, $MJ\ m^{-2}\ h^{-1}$, $W\ m^{-2}$

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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)

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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).

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PART 1
BASIC CONCEPTS

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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).