

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.



ENVIRONMENTAL &
WATER RESOURCES
INSTITUTE

ASCE Manuals and Reports on Engineering Practice No. 70

Evaporation, Evapotranspiration, and Irrigation Water Requirements

Second Edition

Prepared by the
Task Committee on Revision of Manual 70

Edited by
Marvin E. Jensen, Ph.D., NAE
Richard G. Allen, Ph.D., P.E.

Sponsored by the
Committee on Evapotranspiration in Irrigation
and Hydrology of the Irrigation and Drainage Council of the
Environmental and Water Resources Institute of the
American Society of Civil Engineers

ASCE



Published by the American Society of Civil Engineers

Library of Congress Cataloging-in-Publication Data

Names: Jensen, Marvin Eli, 1926- editor. | Allen, R. G. (Rick G.), editor. | American Society of Civil Engineers. Task Committee on Revision of Manual 70. | Environmental and Water Resources Institute (U.S.). Committee on Evapotranspiration in Irrigation and Hydrology

Title: Evaporation, evapotranspiration, and irrigation water requirements/prepared by the Task Committee on Revision of Manual 70 ; edited by Marvin E. Jensen, Ph.D., NAE, Richard G. Allen, Ph.D., P.E. ; sponsored by the Committee on Evapotranspiration in Irrigation and Hydrology of the Irrigation and Drainage Council of the Environmental and Water Resources Institute of the American Society of Civil Engineers.

Other titles: Evapotranspiration and irrigation water requirements.

Description: Second edition. | Reston, Virginia : American Society of Civil Engineers, [2016] | Series: ASCE manuals and reports on engineering practice ; No. 70 | Includes bibliographical references and index.

Identifiers: LCCN 2015011931 | ISBN 9780784414057 (print : alk. paper) | ISBN 9780784479200 (ebook)

Subjects: LCSH: Evapotranspiration—Handbooks, manuals, etc. | Crops—Water requirements—Handbooks, manuals, etc. | Irrigation water—Handbooks, manuals, etc. | Irrigation—Planning—Handbooks, manuals, etc.

Classification: LCC S600.7.E93 E93 2016 | DDC 631.5/87—dc23 LC record available at <http://lcn.loc.gov/2015011931>

2015011931

Published by American Society of Civil Engineers

1801 Alexander Bell Drive

Reston, Virginia, 20191-4382

www.asce.org/bookstore | ascelibrary.org

Any statements expressed in these materials are those of the individual authors and do not necessarily represent the views of ASCE, which takes no responsibility for any statement made herein. No reference made in this publication to any specific method, product, process, or service constitutes or implies an endorsement, recommendation, or warranty thereof by ASCE. The materials are for general information only and do not represent a standard of ASCE, nor are they intended as a reference in purchase specifications, contracts, regulations, statutes, or any other legal document. ASCE makes no representation or warranty of any kind, whether express or implied, concerning the accuracy, completeness, suitability, or utility of any information, apparatus, product, or process discussed in this publication, and assumes no liability therefor. The information contained in these materials should not be used without first securing competent advice with respect to its suitability for any general or specific application. Anyone utilizing such information assumes all liability arising from such use, including but not limited to infringement of any patent or patents.

ASCE and American Society of Civil Engineers—Registered in U.S. Patent and Trademark Office.

Photocopies and permissions. Permission to photocopy or reproduce material from ASCE publications can be requested by sending an e-mail to permissions@asce.org or by locating a title in ASCE's Civil Engineering Database (<http://cedb.asce.org>) or ASCE Library (<http://ascelibrary.org>) and using the "Permissions" link.

Errata: Errata, if any, can be found at <http://dx.doi.org/10.1061/9780784414057>.

Copyright © 2016 by the American Society of Civil Engineers.

All Rights Reserved.

ISBN 978-0-7844-1405-7 (print)

ISBN 978-0-7844-7920-9 (PDF)

Manufactured in the United States of America.

MANUALS AND REPORTS ON ENGINEERING PRACTICE

(As developed by the ASCE Technical Procedures Committee, July 1930, and revised March 1935, February 1962, and April 1982)

A manual or report in this series consists of an orderly presentation of facts on a particular subject, supplemented by an analysis of limitations and applications of these facts. It contains information useful to the average engineer in his or her everyday work, rather than findings that may be useful only occasionally or rarely. It is not in any sense a "standard," however; nor is it so elementary or so conclusive as to provide a "rule of thumb" for nonengineers.

Furthermore, material in this series, in distinction from a paper (which expresses only one person's observations or opinions), is the work of a committee or group selected to assemble and express information on a specific topic. As often as practicable the committee is appointed in the direction of one or more of the Technical Divisions and Councils, and the product evolved has been subjected to review by the Executive Committee of the Division or Council. As a step in the process of this review, proposed manuscripts are often brought before the members of the Technical Divisions and Councils for comment, which may serve as the basis for improvement. When published, each work shows the names of the committees by which it was compiled and indicates clearly the several processes through which it has passed in review, so that its merit may be definitely understood.

In February 1962 (and revised in April 1982), the Board of Direction voted to establish a series titled "Manuals and Reports on Engineering Practice," to include the Manuals published and authorized to date, future Manuals of Professional Practice, and Reports on Engineering Practice. All such Manual or Report material of the Society would have been refereed in a manner approved by the Board Committee on Publications and would be bound, with appropriate discussion, in books similar to past Manuals. Numbering would be consecutive and would be a continuation of present Manual numbers. In some cases of joint committee reports, bypassing of journal publications may be authorized.

A list of available Manuals of Practice can be found at <http://www.asce.org/bookstore>.

This page intentionally left blank

TASK COMMITTEE ON REVISION OF MOP 70

Task Committee

Marvin E. Jensen, Editor	Consultant, Fort Collins, Colorado (formerly Director, Colorado Institute for Irrigation Management, and National Program Leader for Water Management, Agricultural Research Service, USDA)
Richard G. Allen, Editor	Water Resources Engineering Professor, Kimberly Research and Extension Center, University of Idaho, Kimberly
Terry A. Howell	Laboratory Director (retired), Conservation and Research Leader, Conservation and Production Laboratory, Agricultural Research Service, USDA, Bushland, TX
Derrel L. Martin	Professor, Department of Biological Systems, Engineering, University of Nebraska, Lincoln
Richard Snyder	Biometeorologist Specialist, Department of Land, Air, and Water Resources, University of California, Davis
Ivan A. Walter	Principal, Ivon's Engineering, Centennial, CO

BLUE RIBBON REVIEW PANEL

Paul W. Brown	University of Arizona, Tucson
Ronald L. Elliott	University of Oklahoma (retired), Stillwater
Thomas W. Ley	formerly with Colorado Division of Water Resources, Pueblo, now with Natural Resources Consulting Engineers, Fort Collins, CO
Thomas Trout	Agricultural Research Service (retired), USDA, Fort Collins, CO

This page intentionally left blank

DEDICATION



In loving memory of Doris Jensen, 1929–2009, his long 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.

Full text in preview, click buy full

CONTENTS

PREFACE	xii
ACKNOWLEDGMENTS.....	xv
NOTATION	xvii
PART 1: BASIC CONCEPTS	1
1. INTRODUCTION AND HISTORY.....	3
1.1 Introduction to Second Edition	3
1.2 Development of ET and CU Studies in the United States	7
1.3 Revised Edition.....	16
2. EVAPORATION AND EVAPOTRANSPIRATION PROCESSES.....	19
2.1 Introduction	19
2.2 The Water Budget	20
2.3 The Energy Budget	21
2.4 Controlling Factors.....	21
2.5 Estimating Concepts	27
2.6 Measurement Methods.....	29
3. SOIL-PLANT-ATMOSPHERE SYSTEM.....	35
3.1 Introduction	35
3.2 Physical Properties of Water, Water Vapor, and Air	35
3.3 Soil Properties	44
3.4 Soil-Water System	44
3.5 Vegetative (Crop) Properties	54
4. ENERGY BALANCE.....	59
4.1 Introduction	59
4.2 Energy Balance	59

4.3	Net Radiation.....	61
4.4	Soil Heat Flux Density.....	80
5.	SURFACE-ENERGY AND AIR-MASS INTERACTIONS AND THE CONCEPT OF REFERENCE ET	87
5.1	Introduction	87
5.2	Weather and Surface Effects on Conversion of Energy to Latent Heat Flux.....	90
5.3	Standardization of the Vegetative Cover	93
6.	EVAPORATION FROM WATER SURFACES	99
6.1	Introduction	99
6.2	Methods of Estimating Water Surface Evaporation	100
6.3	Example Applications of Evaporation Estimation Methods and Measurements	126
6.4	Summary of Methods for Estimating Evaporation from Water Bodies	135
	PART 2: EVAPOTRANSPIRATION FROM LAND SURFACES	139
7.	WATER AND ENERGY BALANCE COMPONENTS FOR MEASUREMENT AND ESTIMATION	141
7.1	Introduction to Chapters 7–12.....	141
7.2	Volumetric Measurements for Estimating Land Surface ET.....	142
7.3	Mass Balance Methods	149
7.4	Energy Balance Methods—Bowen Ratio	162
7.5	Mass Transfer Method Using Eddy Covariance	168
7.6	Fetch Requirements for Boundary Layer Measurement	172
7.7	Advantages and Disadvantages of ET Measurement Methods.....	175
7.8	Combined Energy Balance and Mass Transfer Methods...	176
8.	REFERENCE CROP ET.....	189
8.1	Introduction	189
8.2	The Penman-Monteith Equation.....	190
8.3	Aerodynamic and Surface Parameters for the PM Equation	192
8.4	Reference ET_{ref} K_c Approach	195
8.5	Missing or Bad Weather Data	206
8.6	Reference ET by Analogy or Association	214
9.	EVAPORATION FROM SOIL.....	221
9.1	Introduction	221
9.2	The Evaporation Process.....	221
9.3	Diurnal Effects and Redistribution of Soil Water.....	222
9.4	Stage 1 Evaporation	223

9.5	Stage 2 Evaporation	225
9.6	Evaporation Models.....	227
9.7	Relationships between Evaporation and Transpiration	240
9.8	Water Balance of the Evaporation Layer.....	243
9.9	Example Estimates of Evaporation.....	245
9.10	Summary	258
10.	CROP COEFFICIENT METHOD	261
10.1	Introduction	261
10.2	The Crop Coefficient.....	261
10.3	Crop (Vegetation Cover) Coefficients	265
10.4	FAO Grass-Based Crop Coefficients	273
10.5	Alfalfa-Based Crop Coefficients	285
10.6	Estimates of K_c Curves for Natural and Agricultural Vegetation.....	287
10.7	Landscape Coefficients.....	294
10.8	Estimates of K_c during Wintertime and Nongrowing Seasons	313
10.9	Summary	321
11.	DIRECT PENMAN-MONTEITH AND AERODYNAMIC ENERGY BALANCE EQUATIONS	323
11.1	Introduction	323
11.2	Common Forms of Resistance-Based Equations	325
11.3	Challenges with Types of Resistance-Based Models	340
11.4	Parameters for the Penman-Monteith for Equivalency with More Complicated Models	342
11.5	Comparative Model Performance.....	343
11.6	Roughness Length and Zero Plane Displacement	345
11.7	Bulk Surface (Stomatal) Resistance.....	355
11.8	Evaporation from Soil and Surface Resistance	379
11.9	Weather Measurements for Direct Application of the Penman-Monteith and AFIB Methods and Reference ET Calculation	387
11.10	Example Applications of the Single-Layer Penman-Monteith.....	396
11.11	Applications of Evapotranspiration Models Using Remote Sensing Inputs	408
11.12	Measurement and Estimation of ET on Sloping Lands	409
11.13	Evaporation of Intercepted Rainfall	410
12.	REGIONAL ESTIMATES OF EVAPOTRANSPIRATION	415
12.1	Introduction	415
12.2	Theory.....	416
12.3	Applications	418

PART 3: WATER REQUIREMENT ESTIMATES	425
13. SELECTION OF APPROPRIATE ESTIMATING METHOD.....	427
13.1 Introduction	427
13.2 Time Frame and Required Accuracy	427
13.3 Input Data Collection, Screening, and Processing	428
13.4 Crop Coefficient Method vs. Direct Methods.....	430
13.5 Evaporation and Evapotranspiration Calculations	431
13.6 Summary	433
14. ESTIMATES OF IRRIGATION WATER REQUIREMENTS AND STREAMFLOW DEPLETION	435
14.1 Introduction	435
14.2 Net Irrigation Water Requirement and Effective Precipitation	435
14.3 Leaching Requirement.....	439
14.4 Miscellaneous Water Requirements	443
14.5 System Losses	445
14.6 Precipitation Runoff.....	451
14.7 Improvements in Estimating Water Requirements.....	454
14.8 Depletions to the Water Resource	455
APPENDIXES	
A. Conversion and Meteorological Tables.....	457
B. Mean Crop Coefficients in Subhumid Climates	471
C. Lengths of Crop Development Stages.....	487
D. Basal Crop Coefficients in Subhumid Climates	499
E. Mean and Basal Crop Coefficients for Crops Common to Temperate and Continental Climates.....	513
F. Basal Crop Coefficients for Crops Common to Temperate and Continental Climates with Thermal Basis.....	523
G. Documentation for Crop Coefficient and ET Data Reporting and Determination of ET from Remote Sensing	543
H. Weather Data Integrity	569
I. Contribution of Capillary Flow from a Shallow Water Table to Evaporation and Evapotranspiration.....	609
J. Derivation of the Penman-Monteith Equation.....	619
K. Regional Estimating Methods and Methods Not Commonly Used in the United States	627
L. Comparison and Ranking of Methods for Estimating ET.....	637
M. Glossary	661
REFERENCES	669
INDEX	733

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

ACKNOWLEDGMENTS

The following organizations and individuals contributed valuable assistance in the research and preparation of the second edition of this manual:

- University of Idaho Research and Extension Center and Idaho Agricultural Experiment Station, Kimberly, ID;
- Agricultural Research Service, U.S. Department of Agriculture, Bushland, TX;
- Agricultural Research Service, U.S. Department of Agriculture, Kimberly, ID;
- 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;
- 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;
- 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 as latent heat flux density, λE	mm d^{-1} , mm h^{-1} $\text{MJ m}^{-2} \text{d}^{-1}$, $\text{MJ m}^{-2} \text{h}^{-1}$, W m^{-2}
E_{pan}	Evaporation rate from Class A pan	mm d^{-1}
EC_e	Electrical conductivity of the saturated soil extract ($1 \text{ mmho cm}^{-1} = 1 \text{ dS m}^{-1}$)	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 as latent heat flux density, λET_o	mm d^{-1} , mm h^{-1} $\text{MJ m}^{-2} \text{d}^{-1}$, $\text{MJ m}^{-2} \text{h}^{-1}$, W m^{-2}
ET_r	ET from a well-watered alfalfa reference crop as latent heat flux density, λET_r	mm d^{-1} , mm h^{-1} $\text{MJ m}^{-2} \text{d}^{-1}$, $\text{MJ m}^{-2} \text{h}^{-1}$, W m^{-2}
ET_{ref}	Reference evapotranspiration, general	mm d^{-1} , mm h^{-1}
G	Heat flux density to the ground	$\text{MJ m}^{-2} \text{d}^{-1}$, $\text{MJ m}^{-2} \text{h}^{-1}$, W m^{-2}
G_{sc}	Solar constant	$\text{MJ m}^{-2} \text{h}^{-1}$, W m^{-2}
H	Heat flux density to the air	$\text{MJ m}^{-2} \text{d}^{-1}$, $\text{MJ m}^{-2} \text{h}^{-1}$, 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	$\text{m}^3 \text{d}^{-1}$
Q_o	Outflow rate	$\text{m}^3 \text{d}^{-1}$
R	Universal gas constant	$\text{kJ kg}^{-1} \text{K}^{-1}$
R	Radiation, general	$\text{MJ m}^{-2} \text{d}^{-1}$, $\text{MJ m}^{-2} \text{h}^{-1}$, W m^{-2}
R_a	Exoatmospheric (extraterrestrial) solar radiation on a horizontal surface	$\text{MJ m}^{-2} \text{d}^{-1}$, $\text{MJ m}^{-2} \text{h}^{-1}$, W m^{-2}
R_b	Net outgoing long-wave radiation	$\text{MJ m}^{-2} \text{d}^{-1}$, $\text{MJ m}^{-2} \text{h}^{-1}$, W m^{-2}
R_{bo}	Net outgoing long-wave radiation on a cloudless day	$\text{MJ m}^{-2} \text{d}^{-1}$, $\text{MJ m}^{-2} \text{h}^{-1}$, W m^{-2}
R_n	Net incoming radiation	$\text{MJ m}^{-2} \text{d}^{-1}$, $\text{MJ m}^{-2} \text{h}^{-1}$, W m^{-2}
R_{nl}	Net outgoing long-wave radiation	$\text{MJ m}^{-2} \text{d}^{-1}$, $\text{MJ m}^{-2} \text{h}^{-1}$, W m^{-2}

(Continued)

(Continued)

Symbol	Definition	Common units
R_{ns}	Net solar radiation	$\text{MJ m}^{-2} \text{d}^{-1}$, $\text{MJ m}^{-2} \text{h}^{-1}$, W m^{-2}
R_s	Solar radiation at the surface on a horizontal plane	$\text{MJ m}^{-2} \text{d}^{-1}$, $\text{MJ m}^{-2} \text{h}^{-1}$, W m^{-2}
R_{so}	Solar radiation on a cloudless day	$\text{MJ m}^{-2} \text{d}^{-1}$, $\text{MJ m}^{-2} \text{h}^{-1}$, W m^{-2}
RH	Relative humidity	%
RH_{max}	Daily maximum relative humidity	%
RH_{min}	Daily minimum relative humidity	%
T	Temperature	$^{\circ}\text{C}$, K , $^{\circ}\text{F}$
T_d	Dew point temperature of the air	$^{\circ}\text{C}$, K
T_{max}	Maximum daily air temperature	$^{\circ}\text{C}$, K
T_{min}	Minimum daily temperature	$^{\circ}\text{C}$, K
T_o	Surface temperature	$^{\circ}\text{C}$, K
T_w	Wet bulb temperature of the air	$^{\circ}\text{C}$, 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	$\text{kJ kg}^{-1} \text{ } ^{\circ}\text{C}^{-1}$
d	Zero plane displacement of wind profile	cm , m
e	Water vapor pressure in air	kPa
e_a	Actual vapor pressure	kPa
e_a^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	
β	Bowen ratio, $=H/\lambda E$	
Γ	Adiabatic lapse rate	$^{\circ}\text{C m}^{-1}$ and K m^{-1}
γ	Psychrometric constant, $\gamma = c_p P / (0.622 \lambda)$	$\text{kPa } ^{\circ}\text{C}^{-1}$
γ^*	Psychrometric constant modified by the ratio of surface resistance to atmospheric resistance, $\gamma^* = \gamma(1 + r_s/r_a)$	$\text{kPa } ^{\circ}\text{C}^{-1}$
Δ	Slope of the saturation vapor pressure-temperature curve, de/dT	$\text{kPa } ^{\circ}\text{C}^{-1}$
Δ	Difference	See usage
ϵ	Emissivity, $\epsilon' =$ net emissivity, $\epsilon_a =$ atmospheric emissivity, and $\epsilon_{vs} =$ vegetative and soil emissivity	

(Continued)

(Continued)

Symbol	Definition	Common units
λE	Latent heat flux density	$\text{MJ m}^{-2} \text{d}^{-1}$, $\text{MJ m}^{-2} \text{h}^{-1}$, W m^{-2}
Θ	Volumetric soil water content	
λ	Latent heat of vaporization	MJ kg^{-1}
π	Pi, $\pi=3.14159$	
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	$\text{kJ m}^{-2} \text{s}^{-1} \text{K}^{-4}$, $\text{MJ m}^{-2} \text{d}^{-1} \text{K}^{-4}$, $\text{W m}^{-2} \text{K}^{-4}$
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).

This page intentionally left blank

PART 1
BASIC CONCEPTS

This page intentionally left blank

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).