Wossenu Abtew · Assefa Melesse

Evaporation and Evapotranspiration

Measurements and Estimations

Springer

Evaporation and Evapotranspiration

Wossenu Abtew • Assefa Melesse

Evaporation and Evapotranspiration

Measurements and Estimations

Springer

Dr. Wossenu Abtew
South Florida Water Management District
West Palm Beach, FL
USA

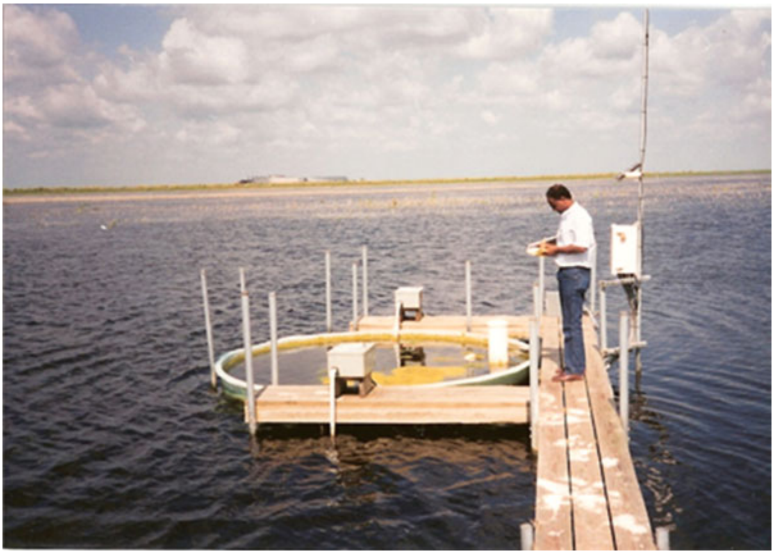
Prof. Dr. Assefa Melesse
Department of Earth and Environment
Florida International University
Miami, FL
USA

ISBN 978-94-007-4736-4 ISBN 978-94-007-4737-1 (eBook)
DOI 10.1007/978-94-007-4737-1
Springer Dordrecht Heidelberg New York London

Library of Congress Control Number: 2012946197

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)



Preface

Water loss through evaporation from open water and evapotranspiration (ET) from vegetation is one of the major components of the hydrologic cycle affecting water resources availability. Measurement and estimation of these terms have initiated the development of the theory of the process, measurement techniques, and estimation equations. Perceptions have contributed to biases of estimation. A drying pond taken over by vegetation gives the perception that the vegetation's increased ET resulted in the drying of the pond. Succession of vegetation in a wetland may hide the impact of changing hydrology by suggesting water losses are due to invading vegetation.

The evapotranspiration process is controlled by the availability of moisture to evaporate. Energy is required to detach water molecules. A mechanism is required to move the vapor into the air column. The air has to have the capacity to hold the vapor. When the air has no more capacity to hold moisture, the reverse process, dew formation, occurs. In this book, dew evaporation is presented in a chapter. A chapter on vapor pressure and vapor pressure deficit estimation methods is presented with known quality data from a monitoring network. ET processes and mechanisms are presented in a simplified way without compromising complexity. In each case, examples of applications from the authors' experience are presented for comparing estimation methods. Meteorological monitoring and data quality, input into ET estimation methods, is vastly discussed in a chapter with illustrations from a large monitoring network. The design and application of a lysimeter system for open water evaporation and wetland vegetation ET has provided measured data to gauge the performance of various estimation equations. The advantage and limitation of simple ET estimation methods, when input data is limited, are addressed. Remote sensing application to ET estimation is sufficiently addressed in three chapters with application case studies. An introduction into the expected impact of climate change on ET rates is included as a chapter with climate model application results. This book is a useful resource for hydrologists, scientists, meteorologists, engineers, water resource managers, agricultural and environmental professionals, students, and teachers.

Wossenu Abtew

Contents

1 Introduction 1
1.1 Overview of Evaporation and Evapotranspiration Studies 1
References 3

2 Meteorological Parameter Monitoring and Data Quality 5
2.1 Introduction 5
2.2 Meteorological Parameters Monitoring Network 5
2.2.1 Sources of Error in Meteorological Parameters 7
2.3 Air Temperature 7
2.3.1 Dew Point Temperature 10
2.4 Humidity 12
2.5 Water Temperature 13
2.6 Atmospheric Pressure 13
2.7 Wind Speed and Wind Direction 15
2.7.1 Wind Profile 18
2.7.2 Wind Barrier's Impact on Wind Speed and Pattern 19
2.8 Solar Radiation 20
2.9 Net Solar Radiation 23
2.10 Summary 27
References 27

3 Evaporation and Evapotranspiration Measurement 29
3.1 Introduction 29
3.2 Pan Evaporation 29
3.3 Lysimeters 32
3.3.1 Weighing Lysimeter 32
3.3.2 Water Balance Lysimeter 32
3.4 Eddy Correlation 37
3.5 Bowen Ratio 38
3.6 Lidar (Light Detection and Ranging Method) 40
3.7 Satellite-Based Methods 41

3.8 Summary 41
References 41

4 Energy Requirements of Dew Evaporation 43
4.1 Introduction 43
4.2 Energy Balance and Transfer Coefficients 44
4.3 Dewfalls and Evaporation 46
4.4 Summary 50
References 51

5 Vapor Pressure Calculation Methods 53
5.1 Introduction 53
5.2 Comparison of Vapor Pressure Computation Methods 54
5.2.1 Methods 54
5.2.2 Results 56
5.3 Summary 61
References 62

6 Evaporation and Evapotranspiration Estimation Methods 63
6.1 Introduction 63
6.2 Simple Methods 64
6.2.1 Pan Method 64
6.2.2 Temperature-Based Methods 65
6.2.3 Radiation-Based Methods 69
6.2.4 Solar Radiation–Maximum Temperature Method 76
6.2.5 Mass Transfer Method 77
6.3 Complex Methods 78
6.3.1 Energy Balance Methods 78
6.3.2 The Penman Method 78
6.4 Remote Sensing Methods 88
6.5 Summary 89
References 89

7 Wetland Evapotranspiration 93
7.1 Introduction 93
7.2 Wetland Evapotranspiration Measurement and Modeling 95
7.2.1 Lysimeters 95
7.2.2 Wetland ET Modeling from Lysimeter Observations 97
7.2.3 Bowen Ratio–Energy Balance Method 100
7.2.4 Penman–Monteith Method 104
7.3 Summary 106
References 107

8 Lake Evaporation 109
8.1 Introduction 109
8.2 Lake Evaporation Estimation Methods 111
8.2.1 Pan Method 111

8.2.2 Water Balance Method ... 112
8.2.3 Energy Balance ... 113
8.2.4 Mass Transfer Method ... 120
8.2.5 The Penman Method ... 123
8.2.6 The Simple Abtew Method ... 125
8.2.7 Solar Radiation–Maximum Temperature Method ... 126
8.2.8 Modified Turc Equation ... 126
8.2.9 Priestley–Taylor Method ... 127
8.2.10 Energy Balance–Bowen Ratio Method (EBBR) ... 127
8.3 Summary ... 129
References ... 130

9 Reference and Crop Evapotranspiration ... 133
9.1 Introduction ... 133
9.2 Reference Evapotranspiration ... 134
9.2.1 Crop Canopy Resistance (r_c) ... 134
9.2.2 Aerodynamic Resistance (r_a) ... 135
9.3 The ASCE Standardized Reference Evapotranspiration Equation . 136
9.4 Potential Evapotranspiration and Evaporation ... 138
9.5 Potential Evapotranspiration from Pan Evaporation ... 138
9.6 Crop Coefficients ... 138
9.7 Summary ... 139
References ... 140

10 Spatially Distributed Surface Energy Flux Modeling ... 141
10.1 Introduction ... 141
10.2 Remotely Sensed Data ... 142
10.2.1 Landsat ... 142
10.2.2 ASTER ... 143
10.2.3 MODIS ... 144
10.3 Surface Energy Budget and Models ... 144
10.3.1 Surface Energy Balance Algorithm for Land (SEBAL) .. 144
10.3.2 Two-Source Energy Balance (TSEB) Model ... 148
10.3.3 Surface Energy Balance System (SEBS) ... 151
10.3.4 Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC) ... 154
10.3.5 Simplified Surface Energy Balance (SSEB) ... 155
10.3.6 Simplified Surface Energy Balance Index (S-SEBI) ... 156
10.4 Summary ... 156
References ... 157

11 Crop Yield Estimation Using Remote Sensing and Surface Energy Flux Model ... 161
11.1 Introduction ... 161
11.2 Surface Energy Flux Budget ... 163

11.3 Case Study ... 164
11.3.1 Data ... 165
11.3.2 Results and Discussion ... 168
11.4 Summary ... 172
References ... 174

12 Wetland Restoration Assessment Using Remote Sensing- and Surface Energy Budget-Based Evapotranspiration ... 177
12.1 Introduction ... 177
12.2 Case Studies ... 179
12.2.1 Glacial Ridge Prairie Restoration ... 179
12.2.2 Kissimmee River Restoration ... 182
12.3 Methodology ... 184
12.3.1 Satellite Image Preprocessing ... 184
12.3.2 Evapotranspiration Mapping ... 184
12.4 Results and Discussion ... 185
12.4.1 Glacial Ridge ... 185
12.4.2 Kissimmee River Basin ... 188
12.5 Summary ... 191
12.5.1 Glacial Ridge ... 191
12.5.2 Kissimmee River Basin ... 192
References ... 194

13 Climate Change and Evapotranspiration ... 197
13.1 Introduction ... 197
13.2 Climate Change and Evapotranspiration ... 198
13.3 Summary ... 201
References ... 201

Index ... 203

Symbols and Abbreviations

A	Area
a, b	Coefficients
AET	Actual ET
a_w, b_w	Coefficients
c	Adjustment factor
c_1, c_2, c_3, c_4	Coefficients
C_{et}	Reference crop coefficient
C_n, C_d	Coefficients
c_p, C_p	Specific heat of air, heat capacity of air
c_s	Soil or water heat capacity
d	Displacement height
d_{TM}	Constant (0.1238 $mWcm2sr^{-1}\mu m^{-1}$)
de	Change in vapor pressure
$d_{e\text{-}s}$	Relative distance between Earth and Sun in astronomical units
DN	Digital number
d_r	Inverse squared relative distance between Earth and Sun
d_s	Effective depth
dT	Change in temperature between two measurement heights
ΔT	Change in temperature
d*t*	Change in time
d*u*	Change in wind speed
d_w	Water depth
d*z*	Change in wind speed measurement height
e	Errors
E, LE	Vapor flux, latent heat flux, evaporation
e_d	Actual vapor pressure
e_{dd}	Vapor pressure in the air above evaporating surface
elev	Elevation above sea level
E_L	Lake evaporation
E_o	Open water evaporation
e_o	Saturation vapor pressure at lake surface

E_p	Potential evaporation
E_{pan}	Pan evaporation
e_s, e_a	Saturation vapor pressure
e_{ss}	Vapor pressure at evaporating surface
ESUN	The mean solar exoatmospheric irradiance
ET	Evapotranspiration
ET_{24}	Daily ET from remotely sensed instantaneous ET
ET_{aero}	Aerodynamic component ET
ET_c	Actual crop evapotranspiration
ET_{frac}	ET fraction for each pixel (average of hot and cold pixels)
ET_i	Remotely sensed instantaneous ET
ET_o	Evapotranspiration from grass reference crop (8 to 15 cm and well watered)
E_p	Potential evaporation
ET_p	Potential evapotranspiration
ET_r	Reference crop evapotranspiration; grass reference ET
ET_{rad}	Radiation component ET
ET_{ref}	Reference ET
ET_r F	Alfalfa reference evapotranspiration fraction
ET_{sz}	Standardized reference crop evapotranspiration for short or tall crop
f	Fractional vegetation cover
$f(u)$	Function of the horizontal wind
F_c	Fraction of cover
f_c	Fractional canopy cover
G	Heat storage
GAIN	Solar spectral radiance for each band
g_b	Boundary layer conductance
g_c	Canopy conductance
g_m	Measured conductance of leaf
g_s	Stomatal conductance in mmol m^{-2} s^{-1}
G_{sc}	Solar constant
g_{sv}	Stomatal conductance in mm s^{-1}
H	Sensible heat
h	Reference vegetation height
h_c	Average height of cover or crop height
H_s	Sensible heat for soil surface
H_v	Sensible heat for vegetation surface
I	Inflow
J	Julian day
k	Von Karman constant
K_1, K_2, K_3	Coefficients
K_{1ls}, K_{2ls}	Calibration constants for Landsat 5 and 7
K_c	Crop coefficient
k_h	Coefficient for sensible heat transfer
k_m	Mass transfer limiting term

K_p	pan coefficient
K_t	Transfer coefficient
k_w	Coefficient for latent heat transfer
L	Obukhov length
LAI	Leaf area index
LE_s	Latent heat for soil surface
LE_v	Latent heat for vegetation surface
L_j	Leaf area index for canopy strata j
L_{max}	Maximum spectral radiance
L_{min}	Minimum spectral radiance
m	Constant ($0.0056322\ mWcm^2sr^{-1}\mu m^{-1}$)
MSE	Mean square error
n/N	Mean actual to possible sunshine ratio
NDVI	Normalized Difference Vegetation Index
NDVs	Scaled NDVI
NIR	Near infrared band
N_o	Mass transfer coefficient
NTC	Negative temperature coefficient
O	Outflow
P	Atmospheric pressure
p	Mean daily percentage total annual daytime hours
PRT	Platinum resistance thermometer
PTC	Positive temperature coefficient
q	Specific humidity
q'	Specific humidity fluctuation
Q_a	Advective energy gain or loss
Q_h	Sensible heat gain or loss
Q_{in}	Energy input into the system
Q_{out}	Energy leaving the system
Q_{Rn}	Energy from net solar radiation
r	Correlation coefficient
R	Linear function of the digital number (DN)
R_A	Extraterrestrial solar radiation
r_a	Aerodynamic resistance
R_b, R_L	Net back or outgoing thermal radiation
r_c	Canopy resistance
RED	Red band
R_f	Rainfall
RH	Relative humidity
RH_{avg24}	Average humidity from 24-h continuous observations
RH_{max}	Daily maximum relative humidity
RH_{min}	Daily minimum relative humidity
r_l	Stomatal resistance of a single leaf
R_n, R_{Sn}	Net solar radiation

$R_{n,s}$	Net solar radiation on soil surface
$R_{n,v}$	Net solar radiation on vegetation surface
R_s	Incoming solar radiation
r_s	Stomatal resistance
R_s	Resistance to heat flow in the boundary layer immediately above the soil surface
R_{so}	Clear sky solar radiation
R_x	Ground reflectance for band x
S	Slope
S_{cj}	Stomatal conductance of leaf strata j
Sp	Seepage
Std	Standard deviation
$S_{y/x}$	Standard error
T	A given temperature
T_a	Air temperature over a lake, near surface air temperature
T_{avg}	Average air temperature
T_{avg24}	Average temperature from 24-h continuous observations
T_d	Dew point temperature
T_{max}	Daily maximum air temperature
T_{min}	Daily minimum air temperature
T_n	Average temperature on day n
T_{n-1}	Average temperature on previous day
T_s	Lake surface water temperature
T_{sur}	Radiometric surface temperature
T_v	Vegetation surface temperature
u^*	Friction velocity or shear velocity
u_{day}	Daytime wind speed
u_z	Wind speed at height z
vpd, δe	Vapor pressure deficit
w	Vertical wind speed
w'	Vertical wind speed fluctuation
WI	Wetness index
z_h	Roughness length for heat transfer
z_o/z_{om}	Aerodynamic roughness/ roughness height or length for momentum transfer
z_{oh}	Roughness length for vapor and heat transfer
α	Albedo
$\alpha_{path\text{-}radiance}$	Path radiance albedo
α_{toa}	Albedo of the top of atmosphere
β	Bowen ratio
γ	Psychrometric constant
δ	Change in depth
Δ	Slope of vapor pressure curve
Δe	Change in vapor pressure
ΔQ_s	Change in energy storage

ΔS	Change in storage
ΔSM	Change in soil moisture
ΔT	Change in temperature with time
ε	Ratio of molecular weight of water to dry air
ε_a	Atmospheric emissivity
ε_s	Surface emissivity
ζ_{short}	Absorptivity
Θ*	Temperature scale
θ, sδ	Solar declination angle in radians
θ_a	Potential air temperature at height z
θ_o	Potential temperature at the surface
$\theta_o - \theta_a$	Mean surface temperature
θ_v	Potential virtual temperature near the surface
λ	Latent heat of vaporization of water
Λ_r	Relative evaporative fraction
λ_s	Thermal conductivity of soil
ρ	Air density
Γ_c	Coefficient
Γ_v	Coefficient
σ	Stefan–Boltzmann constant
τ	Shear stress
τ_o	Surface shear stress
τ_{sw}	One-way atmospheric transitivity
φ	Latitude in radians
Ψ_h	Stability correction factor/function for sensible heat transfer
Ψ_m	Stability correction factor/function for momentum transfer

Chapter 1
Introduction

1.1 Overview of Evaporation and Evapotranspiration Studies

Evaporation from open water and wet surfaces and evapotranspiration from vegetation are one of the major parameters in the hydrologic cycle. Most precipitation is lost in the form of evaporation and evapotranspiration with the percentage varying from region to region globally. Spatial variation by latitude, longitude, altitude, environment, and specific site conditions is a source of variation in evaporation and potential evapotranspiration. Standardized measurement and estimation of this parameter are challenging. Even with estimation methods standardized, variation in estimates would occur due to lack of uniformity in input data collection and quality control. A positive characteristic of this parameter is that it has relatively smaller variation for a given time and location. Seasonal fluctuations are known, and ranges are limited when water is not a limiting factor. Estimation error is relatively lower if appropriate equation and good quality input data is used for a given site.

Apart from individual publications on the subject, the United Nations Food and Agriculture Organization (FAO) and the American Society of Civil Engineers (ASCE) have made major contributions toward developing common understanding of the science of evaporation and evapotranspiration and standardizing estimation methods. ASCE's consumptive use of water and irrigation requirements (Jensen 1973) provided the most detailed information on evapotranspiration for that period with various evapotranspiration and potential evapotranspiration estimation methods documented and evaluated. FAO Irrigation and Drainage Paper No. 24, Crop Water Requirements (Doorenbos and Pruitt 1977) presented the Blaney–Criddle, Penman, and pan evaporation methods for estimating reference crop evapotranspiration. The presentation is organized for wide-scale application with tables and charts. Crop coefficients are provided for various crops. Irrigation scheduling guidance is also provided with application rate estimations. ASCE manual and reports on engineering practice No. 70, Evapotranspiration and Irrigation Water Requirements

W. Abtew and A. Melesse, *Evaporation and Evapotranspiration: Measurements and Estimations*, DOI 10.1007/978-94-007-4737-1_1,

(Jensen et al. 1990) build on past publications and provide details on methods and parameter estimations. Methods are evaluated using lysimeter-measured evapotranspiration data from various locations. Distinction is presented between potential and reference evapotranspiration. Crop coefficients are provided for various crops including varying by stage of crop growth. The ASCE Standardized Reference Evapotranspiration Equation (Allen et al. 2005) was published for standardizing reference evapotranspiration estimation methods by providing a single equation with common procedures to derive or estimate certain inputs. The American Society of Agricultural and Biological Engineers dedicated periodic conferences on evaporation and irrigation scheduling producing conference proceedings that contributed to the advancement of the science and application to agriculture.

This book builds on existing works on the subject but introduces a fresh and new approach. Topics as lake evaporation and wetland evapotranspiration have not been given this scale of analysis in the past. Each is presented in a chapter. Lysimeter measurements are used to demonstrate application of various methods. New simplified equations are presented. Estimation of evapotranspiration depends on the quality of input data. This book sufficiently covers meteorological monitoring and data quality based on experience of meteorological data collection. The quality of evapotranspiration estimates is dependent both on the selected model and the quality of the input data. While most publications intensively evaluate ET estimation equations, input data quality is not sufficiently evaluated. In most cases, input data sources are external, and data quality is not available with the data. In this book, a chapter is devoted to meteorological parameter monitoring, sensors, challenges in acquiring good quality data, and data quality evaluation. Illustrations of poor and good data quality are provided.

Evaporation and evapotranspiration measurements are presented from the simple pan to remote sensing methods. Remote sensing application to evapotranspiration quantification is covered in three chapters covering presentation of the various surface energy balance models utilizing remotely sensed data, application of remotely sensed based ET for crop yield estimation, and also evaluation of wetland restorations. Case studies demonstrating the application of remote sensing are presented.

Dew formation and the energy required to evaporate dew are presented in a chapter with results from experimental work. Energy balance and mass transfer during early morning dew evaporation are discussed in full detail. A chapter is devoted to evaluation of many types of vapor pressure calculation methods using quality-controlled meteorological data collection. A review of global warming and climate change projected impact on rates of evapotranspiration is explored in a chapter with literature review and model applications.

There are global, regional, local, and site-specific evapotranspiration estimation products provided by commercial, governmental, and academic institutions. In several cases, graphic and digital products are provided with not much explanation in what equations and data were used to generate the product. Nevertheless, the products satisfy various needs. A global average actual evaporation monthly product developed from meteorological data input of 1985 to 1999 based on the JULES model is available on the web (http://www.jchmr.org/jules. Accessed on 13 October 2011). JULES output is based on simulation of evaporation from soil and canopy as well as the surface of lakes, wet vegetation canopies, and snow. High evaporation in May in the northern hemisphere and in February in the southern hemisphere is shown. It illustrates globally that evaporation is limited by moisture availability and by the variables that affect evaporation.

Annual average potential evapotranspiration estimates for the continental United States are posted on the web (http://serc.carleton.edu/images/introgeo/socratic/examples/USevapotran.jpg. Accessed 13 October 2011). Global monthly evaporation total and anomalies are provided by the National Oceanic and Atmospheric Administration (http://www.cpc.ncep.noaa.gov/cgi-bin/gl_Evaporation-Monthly.sh. Accessed 05 December 2011). A reference evapotranspiration map for Africa is provided by the Food and Agriculture Organization (FAO) of the United Nations. The reference evapotranspiration data is derived using the FAO Penman–Monteith method as described in FAO Drainage Paper 56 (Allen et al. 1998) at a web site (http://www.fao.org/nr/water/aquastat/watresafrica/index3.stm. Accessed 13 October 2011).

Annual areal potential evapotranspiration estimates for Australia are provided by the Australian Bureau of Meteorology. Areal evapotranspiration is computed based on Morton's (1983) complementary relationship areal evapotranspiration model. Morton's model for areal evapotranspiration is a modified Priestley–Taylor equation with modification for advection (Wang et al. 2001). Caution is added in the documentation that the ET map is subject to error from input data measurement error, sampling error, interpolation and mapping error, and model error. The map can be accessed on the web (http://www.bom.gov.au/jsp/ncc/climate_averages/evapotranspiration/index.jsp?maptype=3&period=an. Accessed 13 October 2011).

Evaporation and evapotranspiration estimation is presented in this book in a chapter in detail with application of simple to complex models. Model comparison is presented with input meteorological data of known quality. Selection of the best estimation model for a location with limited input data sets is made simpler. Reference and crop evapotranspiration is presented in a chapter making the link between reference evapotranspiration and actual crop evaporation. All 13 chapters contain valuable material for reference and applications.

References

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration – guidelines for computing crop water requirements. FAO irrigation and drainage paper 56. FAO, Rome

Allen RG, Walter IA, Elliott R, Howell T, Itenfsu D, Jensen M (2005) The ASCE standardized reference evapotranspiration equation. ASCE, Reston

Doorenbos J, Pruitt WO (1977) Guidelines for predicting crop water requirements. FAO irrigation and drainage paper 24. FAO, Rome

Jensen ME (1973) Consumptive use of water and irrigation water requirements. ASCE, New York