

Developments in Atmospheric Science 22

R. BURMAN AND L.O. POCHOP

Evaporation, Evapotranspiration and Climatic Data

Developments in Atmospheric Science, 22

EVAPORATION, EVAPOTRANSPIRATION AND CLIMATIC DATA

R. BURMAN
L.O. POCHOP

*University of Wyoming
Department of Civil and Architectural Engineering
College of Engineering
P.O. Box 3295
Laramie, Wyoming 82071-3295
U.S.A.*

301/3706 INSTITUT
PUR METEOROLOGIE U. KLIMATOLOGIE
UNIVERSITÄT HANNOVER
HERRENHÄUSER STR. 2 - 30419 HANNOVER



ELSEVIER
Amsterdam – Lausanne – New York – Oxford – Shannon – Tokyo 1994

Table of Contents

Chapter 1 Introduction	1
1.1 Definitions of evapotranspiration and transpiration	2
1.1.1 <i>Symbols, variables and units</i>	3
1.2 Measurement of evapotranspiration	4
1.2.1 <i>Soil water budget methods</i>	5
1.2.2 <i>Soil water measurement</i>	6
1.2.3 <i>Hydrologic budget methods</i>	6
1.2.4 <i>Lysimetric measurement</i>	7
1.2.5 <i>Indirect meteorological methods</i>	8
1.2.6 <i>Chamber techniques</i>	8
1.2.7 <i>Biological methods</i>	9
1.2.8 <i>Passive methods</i>	9
1.3 Estimating E or ET using climatic data	9
1.3.1 <i>Estimation of water surface evaporation</i>	10
1.3.2 <i>Direct estimation methods</i>	10
1.3.3 <i>Methods using potential or reference crop ET</i>	10
1.3.4 <i>Methods calculating separate soil evaporation and transpiration</i>	10
Chapter 2 Atmospheric & thermodynamic parameters	13
2.1 Wind profiles and relationships	13
2.1.1 <i>Time dependency of wind measurements and units</i>	13
2.1.2 <i>Wind profile relationships</i>	15
2.1.3 <i>Atmospheric stability</i>	16
2.1.4 <i>Determining wind speed at different elevations</i>	18
2.2 Thermodynamic parameters	19
2.2.1 <i>Atmospheric pressure, P and density, ρ</i>	19
2.2.2 <i>Atmospheric humidity calculations</i>	22
2.2.3 <i>Vapor pressure e</i>	22
2.2.4 <i>Slope of vapor pressure and temperature relationship Δ</i>	23
2.2.5 <i>Relative humidity RH</i>	24
2.2.6 <i>Mixing ratio r</i>	24
2.2.7 <i>Specific humidity q</i>	24
2.2.8 <i>Psychrometer measurements and equation</i>	25
2.2.9 <i>Actual vapor pressure e_a</i>	26
2.2.10 <i>Specific heat at constant pressure C_p</i>	26
2.2.11 <i>Latent heat of vaporization λ</i>	27
2.2.12 <i>Psychrometric coefficient γ</i>	27
2.3 Radiation	28
2.3.1 <i>Solar radiation R_s</i>	29

2.3.2 Vertical energy balance	29
2.3.3 Solar constant SC	29
2.3.4 Albedo α	29
2.3.5 Constant albedo	31
2.3.6 Variable albedo model	32
2.3.7 Sun-earth geometric relationships	32
2.3.8 Declination of the sun δ	35
2.3.9 Cooper declination model	36
2.3.10 Burman-Jacquot declination model	36
2.3.11 Variations in the sun-earth distance $\left[\frac{\bar{d}}{d} \right]^2$	37
2.3.12 Duffie-Beckman sun-earth distance correction	37
2.3.13 Day length predictions	38
2.3.14 Percent daytime hours p	38
2.3.15 Extraterrestrial radiation R_a	38
2.3.16 Clear day solar radiation R_{so}	40
2.3.17 Tabular estimates of clear day solar radiation R_{so}	40
2.3.18 ASHRAE clear day radiation model R_{so} (instantaneous)	41
2.3.19 Heermann et al. daily estimates R_{so}	43
2.4 Solar radiation R_s	46
2.5 Net radiation R_n	48
2.5.1 Net radiation estimation R_n	48
2.5.2 Net long wave radiation using Brunt equation	49
2.5.3 Constant coefficients for Brunt equation	49
2.5.4 Variable coefficients for Brunt equation	50
2.5.5 Net long wave radiation R_{nl} using component approach	51
2.6 Soil heat flux	54
2.6.1 Daily model	54
2.6.2 Ten day to monthly model	55
Chapter 3 Soil parameters	57
3.1 Soil water fundamentals	57
3.1.1 Energy status of soil water	57
3.1.2 Gravity potential	58
3.1.3 External pressure potential	58
3.1.4 Matric potential	59
3.1.5 Osmotic potential	59
3.1.6 First law of thermodynamics	59
3.2 Soil water reference points	61
3.2.1 Saturation	61
3.2.2 Drained upper limit or field capacity	62

3.2.3 <i>Lower limit or wilting point</i>	62
3.3 Soil water storage	64
3.3.1 <i>Plant extractable soil water (available soil water)</i>	64
3.3.2 <i>Readily available soil water, RAM</i>	65
3.3.3 <i>Management allowed deficiency MAD</i>	65
3.3.4 <i>Typical soil water capacities</i>	66
3.3.5 <i>Field soil water and water table conditions.</i>	67
3.4 Soil water influences on plant growth	68
3.5 Soil water movement	68
3.5.1 <i>Darcy's law</i>	69
3.5.2 <i>Hydraulic conductivity</i>	70
3.5.3 <i>Intrinsic permeability</i>	70
3.5.4 <i>Saturated soil water movement</i>	70
3.5.5 <i>Unsaturated soil water movement</i>	70
3.6 Soil water supply for evapotranspiration	71
3.6.1 <i>Stored soil water</i>	71
3.6.2 <i>Natural precipitation</i>	71
3.6.3 <i>Non-growing season precipitation</i>	71
3.6.4 <i>Growing season precipitation</i>	72
3.6.5 <i>Water supplied by irrigation</i>	72
3.6.6 <i>Movement to or from a water table</i>	72
 Chapter 4 Estimating reference crop ET	73
4.1 Sequence of calculations and flow charts	74
4.2 Potential ET and/or reference crop ET	74
4.3 Crop coefficients	75
4.4 Penman methods	75
4.4.1 <i>Penman correction factor c</i>	76
4.4.2 <i>Penman wind functions</i>	77
4.4.3 <i>Seasonally constant wind functions</i>	78
4.4.4 <i>Seasonally variable wind function</i>	78
4.4.5 <i>Vapor pressure deficit term f(e) or VPD</i>	79
4.4.6 <i>VPD, vapor pressure averaging</i>	79
4.4.7 <i>VPD, temperature averaging</i>	80
4.4.8 <i>Penman method flow chart</i>	80
4.4.9 <i>Specific Penman calibrations</i>	80
4.4.10 <i>1963 Penman (original)</i>	81
4.4.11 <i>Penman equation, Wright and Jensen 1972</i>	81
4.4.12 <i>Penman equation, Wright 1982</i>	82
4.4.13 <i>FAO-24 Doorenbos and Pruitt, Penman method</i>	83
4.5 Penman-Monteith method	86
4.5.1 <i>General Penman-Monteith method</i>	86
4.5.2 <i>General aerodynamic resistance r_a</i>	87
4.5.3 <i>Basis for aerodynamic resistance equations</i>	87

4.5.4 Neutral atmospheric conditions	88
4.5.5 Unstable atmospheric conditions	88
4.5.6 Other aerodynamic expressions	88
4.5.7 General plant resistance term r_c	89
4.5.8 Penman-Monteith reference or potential ET	89
4.5.9 Direct estimates of ET using the Penman-Monteith model	90
4.5.10 Penman-Monteith method flow charts	91
4.6 Radiation methods	91
4.6.1 Jensen-Haise method	91
4.6.2 Makkink and FAO-24 radiation methods	93
4.7 Temperature methods	94
4.7.1 Original Blaney-Criddle method	94
4.7.2 SCS Blaney-Criddle method	95
4.7.3 FAO-24 Blaney-Criddle method	95
4.8 Radiation and temperature methods flow charts	98
4.9 Estimating reference ET using measured pan evaporation	98
4.9.1 Pan evaporation as an index of ET	98
4.9.2 Evaporation pans compared to vegetation and open water	100
4.9.3 Types of pans	101
4.9.4 Operation of evaporation pans	102
4.9.5 Limitations of evaporation pan data	102
4.9.6 Christiansen method using pan evaporation	103
Chapter 5 Estimating ET for specific crops	105
5.1 ET using ET_r	106
5.2 Botanic and cultural influences	106
5.2.1 Growth cycles	107
5.2.2 Reference or potential ET	109
5.2.3 Soil influences	109
5.3 Soil water and ET estimates	110
5.3.1 Water depletion & field conditions	112
5.3.2 Soil profile subdivisions	114
5.3.3 Zone of ET removal	115
5.3.4 Measured root density	116
5.3.5 Linear relationships	117
5.3.6 Step soil water corrections based on depletion	117
5.3.7 Natural logarithmic relationships	118
5.3.8 Other curvilinear relationships	119
5.3.9 Composite and other relationships	120
5.4 Crop curves	122
5.4.1 Basal crop coefficients	123
5.4.2 Average crop coefficients	123

5.5 Grass-related crop coefficients	124
5.6 Alfalfa-related crop coefficients	133
5.6.1 <i>Use of alfalfa-related average crop coefficients, K_c</i>	135
5.6.2 <i>Use of alfalfa-related basal crop coefficients, K_{cb}</i>	139
5.6.3 <i>Wet soil surface</i>	143
5.7 Estimation of crop ET without formal ET _r	143
5.7.1 <i>Blaney-Criddle method</i>	144
5.7.2 <i>SCS Blaney-Criddle method</i>	146
5.7.3 <i>Penman-Monteith method</i>	147
5.7.4 <i>Flow chart for direct estimation of ET</i>	150
5.8 Separate estimation of E _s and T	151
5.8.1 <i>Soil evaporation</i>	151
5.8.2 <i>Inclusion of growing vegetation</i>	156
5.8.3 <i>Transpiration</i>	158
5.8.4 <i>Residues</i>	159
5.8.5 <i>Stubbles</i>	160
5.8.6 <i>Adaptations for winter conditions</i>	161
5.9 Irrigation water requirements	162
5.10 Components of irrigation water requirements	162
5.10.1 <i>The determination of evapotranspiration</i>	163
5.10.2 <i>Other components of irrigation water requirements</i>	163
5.11 Sources of water for crop growth	164
5.12 Soil water storage of natural precipitation	164
5.12.1 <i>Effective precipitation</i>	165
5.12.2 <i>Effective precipitation and area</i>	166
5.12.3 <i>Effective precipitation and specific crops</i>	167
5.12.4 <i>Growing season effective precipitation</i>	167
5.13 Non-growing season precipitation	170
5.13.1 <i>Irrigation water from shallow water tables</i>	171
 Chapter 6 Production, vegetation & ET	173
6.1 Uses of production functions	173
6.2 Defining assumptions	173
6.2.1 <i>Seasonal assumptions</i>	174
6.2.2 <i>Functional limitations</i>	174
6.3 Common models	174
6.3.1 <i>Linear relationships</i>	174
6.3.2 <i>Production reduction ratio</i>	176
6.3.3 <i>Measured production reduction related to relative ET</i>	176
6.4 Transferability issues	178
6.5 Sequence of calculations	178
6.5.1 <i>Selection of crop water production functions</i>	180
6.5.2 <i>Maximum production</i>	181
6.5.3 <i>Maximum evapotranspiration</i>	181

<i>6.5.4 Existence evapotranspiration</i>	181
<i>6.6 Flow chart for estimating vegetative production</i>	182
 Chapter 7 Evaporation from water surfaces	183
<i>7.1 Methods</i>	184
<i>7.1.1 Kohler-Nordenson-Fox equation</i>	184
<i>7.1.2 Kohler-Parmele equation</i>	186
<i>7.1.3 Priestley-Taylor equation</i>	188
<i>7.1.4 Stewart-Rouse equation</i>	188
<i>7.1.5 deBruin equation</i>	189
<i>7.1.6 Linacre equation</i>	190
 Chapter 8 Comparisons and example calculations	191
<i>8.1 Introduction</i>	191
<i>8.2 Example calculations</i>	191
<i>8.2.1 Significant figures</i>	192
<i>8.2.2 Conversion between energy and depth units</i>	193
<i>8.2.3 SI unit principles</i>	193
<i>8.3 Chapter 2 examples</i>	194
<i>8.3.1 Constant parameters</i>	194
<i>8.3.2 Thermodynamic & atmospheric parameters</i>	195
<i>8.3.3 Net radiation examples</i>	203
<i>8.4 Chapter 4 examples</i>	204
<i>8.4.1 Input data & parameters</i>	204
<i>8.4.2 Constant parameters</i>	205
<i>8.4.3 Original Penman method</i>	206
<i>8.4.4 Penman equation, Wright and Jensen 1972 examples</i>	207
<i>8.4.5 Penman equation, Wright 1982 examples</i>	208
<i>8.4.6 FAO Penman</i>	209
<i>8.4.7 Penman-Monteith equation reference ET examples</i>	210
<i>8.4.8 Jensen-Haise method</i>	212
<i>8.4.9 FAO-24 radiation method (Makkink)</i>	212
<i>8.4.10 FAO-24 Blaney-Criddle method examples</i>	213
<i>8.5 Chapter 5 examples</i>	214
<i>8.5.1 FAO-24 Crop Coefficients</i>	215
<i>8.5.2 ASCE Crop Coefficients</i>	216
<i>8.6 Chapter 7 examples</i>	220
<i>8.6.1 Evaporation units and input data</i>	221
<i>8.6.2 General parameters</i>	221
<i>8.6.3 Kohler-Nordenson-Fox equation</i>	222
<i>8.7 Property standards</i>	223
<i>8.7.1 Atmospheric pressure</i>	223
<i>8.7.2 Vapor pressure</i>	226
<i>8.7.3 Latent heat of vaporization</i>	231

8.7.4 Psychrometer coefficient γ	235
8.7.5 Psychrometer derivation	235
8.7.6 specific heat	236
8.8 Sun-earth relationships	237
8.8.1 Sun-earth geometry	238
8.8.2 Yearly variations in sun-earth geometry	238
8.8.3 Declination	239
8.8.4 Cooper model δ	239
8.8.5 Burman and Jacquot model δ	240
8.8.6 Spencer model δ	240
8.8.7 Stine and Harrigan model δ	240
8.8.8 Day-length	241
8.8.9 Percent daytime	241
8.8.10 Earth-sun distance correction	242
8.8.11 Duffie-Beckman model	242
8.8.12 Spencer distance correction	242
8.8.13 Extraterrestrial solar radiation	243
8.8.14 Clear day solar radiation	243
8.9 Comparisons with standard values	244
8.9.1 Statistical and numerical comparisons	244
8.9.2 Declination comparisons	245
8.9.3 Earth-sun distance comparisons	246
8.9.4 Day-length comparisons	248
8.9.5 Percent daytime comparisons	248
8.9.6 Extraterrestrial radiation comparisons	250