

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 Lower limit or wilting point	62
3.3 Soil water storage	64
3.3.1 Plant extractable soil water (available soil water)	64
3.3.2 Readily available soil water, RAM	65
3.3.3 Management allowed deficiency MAD	65
3.3.4 Typical soil water capacities	66
3.3.5 Field soil water and water table conditions.	67
3.4 Soil water influences on plant growth	68
3.5 Soil water movement	68
3.5.1 Darcy's law	69
3.5.2 Hydraulic conductivity	70
3.5.3 Intrinsic permeability	70
3.5.4 Saturated soil water movement	70
3.5.5 Unsaturated soil water movement	70
3.6 Soil water supply for evapotranspiration	71
3.6.1 Stored soil water	71
3.6.2 Natural precipitation	71
3.6.3 Non-growing season precipitation	71
3.6.4 Growing season precipitation	72
3.6.5 Water supplied by irrigation	72
3.6.6 Movement to or from a water table	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 Penman correction factor c	76
4.4.2 Penman wind functions	77
4.4.3 Seasonally constant wind functions	78
4.4.4 Seasonally variable wind function	78
4.4.5 Vapor pressure deficit term f(e) or VPD	79
4.4.6 VPD, vapor pressure averaging	79
4.4.7 VPD, temperature averaging	80
4.4.8 Penman method flow chart	80
4.4.9 Specific Penman calibrations	80
4.4.10 1963 Penman (original)	81
4.4.11 Penman equation, Wright and Jensen 1972	81
4.4.12 Penman equation, Wright 1982	82
4.4.13 FAO-24 Doorenbos and Pruitt, Penman method	83
4.5 Penman-Monteith method	86
4.5.1 General Penman-Monteith method	86
4.5.2 General aerodynamic resistance r_a	87
4.5.3 Basis for aerodynamic resistance equations	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 Use of alfalfa-related average crop coefficients, K_c	135
5.6.2 Use of alfalfa-related basal crop coefficients, K_{cb}	139
5.6.3 Wet soil surface	143
5.7 Estimation of crop ET without formal ET_r	143
5.7.1 Blaney-Criddle method	144
5.7.2 SCS Blaney-Criddle method	146
5.7.3 Penman-Monteith method	147
5.7.4 Flow chart for direct estimation of ET	150
5.8 Separate estimation of E_s and T	151
5.8.1 Soil evaporation	151
5.8.2 Inclusion of growing vegetation	156
5.8.3 Transpiration	158
5.8.4 Residues	159
5.8.5 Stubbles	160
5.8.6 Adaptations for winter conditions	161
5.9 Irrigation water requirements	162
5.10 Components of irrigation water requirements	162
5.10.1 The determination of evapotranspiration	163
5.10.2 Other components of irrigation water requirements	163
5.11 Sources of water for crop growth	164
5.12 Soil water storage of natural precipitation	164
5.12.1 Effective precipitation	165
5.12.2 Effective precipitation and area	166
5.12.3 Effective precipitation and specific crops	167
5.12.4 Growing season effective precipitation	167
5.13 Non-growing season precipitation	170
5.13.1 Irrigation water from shallow water tables	171
Chapter 6 Production, vegetation & ET	173
6.1 Uses of production functions	173
6.2 Defining assumptions	173
6.2.1 Seasonal assumptions	174
6.2.2 Functional limitations	174
6.3 Common models	174
6.3.1 Linear relationships	174
6.3.2 Production reduction ratio	176
6.3.3 Measured production reduction related to relative ET	176
6.4 Transferability issues	178
6.5 Sequence of calculations	178
6.5.1 Selection of crop water production functions	180
6.5.2 Maximum production	181
6.5.3 Maximum evapotranspiration	181

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