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Introduction to Hydrology

Fourth Edition

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To Bette and Gayle for their patience, understanding, and help

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Preface

Water management is taking on new dimensions. New federal thrusts, the growing list of global issues, and strong public sentiment regarding environmental protection have been the principal driving forces.

In the early years of the 20th century, water resources development and management were focused almost exclusively on water supply and flood control. Today, these issues are still important, but protecting the environment, ensuring safe drinking water, and providing aesthetic and recreatioinal experiences compete equally for attention and funds. Furthermore, an environmentally conscious public is pressing for greater reliance on improved management practices, with fewer structural components, to solve this nation's water problems. The notion of continually striving to provide more water has been replaced by one of husbanding this precious natural resource.

There is a growing constituency for allocating water for the benefit of fish and wildlife, for protection of marshes and estuary areas, and for other natural system uses. But estimating the quantities of water needed for environmental protection and for maintaining and/or restoring natural systems is difficult, and there are still many unknowns. Scientific data are sparse, and our understanding of the complex interactions inherent in ecosystems of all scales is rudimentary. Indeed, this is a critical issue, since the quantities of water involved in environmental protection can be substantial and competition for these waters from traditional water users is keen. The nations of the world are facing major decisions regarding natural systems—decisions that are laden with significant economic and social impacts. Thus there is an urgency associated with developing a better understanding of ecologic systems and of their hydrologic components.

Water policies of the future must therefore take on broader dimensions. More emphasis must be placed on regional planning and management, and regional institutions to accommodate this must be devised. Water management must be practiced at, and between, all levels of government. Land use and water use planning must be more tightly coordinated as well.

Water scientists and engineers of tomorrow must be equipped to address a diversity of issues such as: the design and operation of data retrieval and storage systems; forecasting; developing alternative water use futures; estimating water requirements for natural systems; exploring the impacts of climate change; developing more efficient systems for applying water in all water-using sectors; and analyzing and designing water management systems incorporating technical, economic, environmental, social, legal, and political elements. A knowledge of hydrologic principles is a requisite for dealing with such issues.

This fourth edition has been designed to meet the contemporary needs of water scientists and engineers. It is organized to accommodate students and practitioners who are concerned with the development, management, and protection of water resources. The format of the book follows that of its predecessor, providing material for both an introductory and a more advanced course.

Parts One through Four provide the basics for a beginning level course, while Parts Five and Six may be used for a more advanced course on hydrologic modeling. This fourth edition has been updated throughout, and many solved examples have been added. In addition, new computer approaches have been introduced and problem-solving techniques include the use of spreadsheets as appropriate. New features of each chapter include an introductory statement of contents and, at the conclusion of the chapter, a summary of key points.

Many sources have been drawn upon to provide subject matter for this book, and the authors hope that suitable acknowledgment has been given to them. Colleagues and students are recognized for their helpful comments and reviews, particularly the following reviewers.

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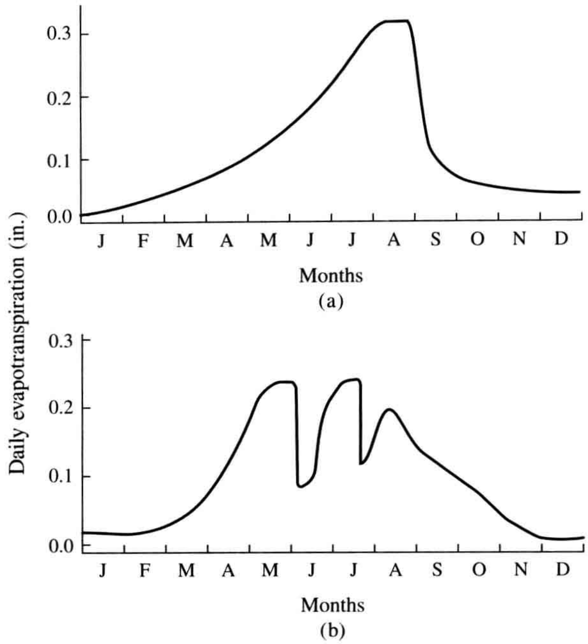

Figure 5.5 Average daily consumption of water: (a) for year 1953 by corn, followed by winter wheat under irrigation; (b) for year 1955, with irrigated first-year meadow of alfalfa, red clover, and timothy. Both measurements taken on lysimeter Y 102 C at the Soil and Water Conservation Research Station, Coshocton, Ohio. (After Holtan et al.[29])

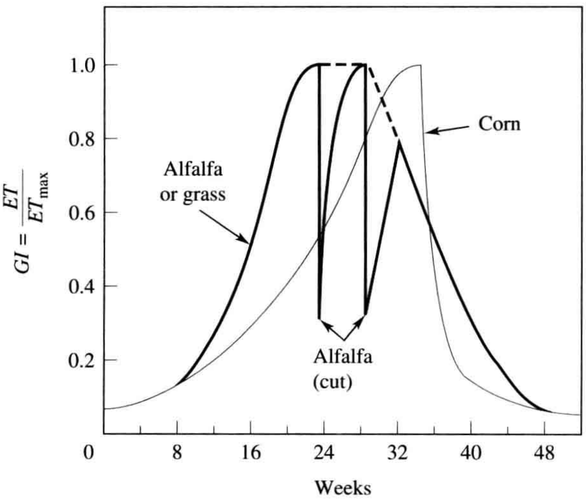

Figure 5.6 Growth index $GI = ET/ET_{\max}$ from lysimeter records, irrigated corn, and hay for 1955, from Coshocton, Ohio. (After Holtan et al.[29])

TABLE 5.5 HYDROLOGIC CAPACITIES OF SOIL TEXTURE CLASSES

Texture class	S^a (%)	G^b (%)	AWC^c (%)	x AWC/G
Coarse sand	24.4	17.7	6.7	0.38
Coarse sandy loam	24.5	15.8	8.7	0.55
Sand	32.3	19.0	13.3	0.70
Loamy sand	37.0	26.9	10.1	0.38
Loamy fine sand	32.6	27.2	5.4	0.20
Sandy loam	30.9	18.6	12.3	0.66
Fine sandy loam	36.6	23.5	13.1	0.56
Very fine sandy loam	32.7	21.0	11.7	0.56
Loam	30.0	14.4	15.6	1.08
Silt loam	31.3	11.4	19.9	1.74
Sandy clay loam	25.3	13.4	11.9	0.89
Clay loam	25.7	13.0	12.7	0.98
Silty clay loam	23.3	8.4	14.9	1.77
Sandy clay	19.4	11.6	7.8	0.67
Silty clay	21.4	9.1	12.3	1.34
Clay	18.8	7.3	11.5	1.58

^aS = total porosity − 15 bar moisture %.
^bG = total porosity − 0.3 bar moisture %.
$^cAWC = S - G$.
Source: Adapted from C. B. England, "Land Capability: A Hydrologic Response Unit in Agricultural Watersheds," U.S. Department of Agriculture, ARS 41–172, Sept. 1970. After H. N. Holtan et al.[29]

The *GI* curves have been developed by expressing experimental data on daily evapotranspiration for several crops (Fig. 5.5) as a percentage of the annual maximal daily rate (Fig. 5.6). Equation 5.26 is used by the Agricultural Research Service in its USDAHL-74 model of watershed hydrology in combination with *GI* curves to calculate daily evapotranspiration. Representative values for *S*, *G*, and *AWC* are given in Table 5.5.

5.7 ESTIMATING EVAPOTRANSPIRATION

Transpiration is an important component in the hydrologic budget of vegetated areas, but it is a difficult quantity to measure because of its dependence on phytological variables. It is a function of the number and types of plants, soil moisture and soil type, season, temperature, and average annual precipitation. As noted previously, evaporation and transpiration are commonly estimated in their combined evapotranspiration form.

If the precipitation and net runoff for an area are known, and estimates of groundwater flow and storage can be made, rough estimates of *ET* can be had using the basic hydrologic equation, Eq. 1.1. A more sophisticated approach developed by Penman follows.[15] It is representative of the methods most often used.

The Penman Method

Both the energy budget and mass transport methods for estimating evapotranspiration (ET) have limitations due to the difficulties encountered in estimating parameters and in making other required assumptions. To circumvent some of these problems, Penman developed a method to combine the mass transport and energy budget theories. This widely used method is one of the more reliable approaches to estimating ET rates using climatic data.[13,15,23,30]

The Penman equation is of the form of Eq. 5.18; it is theoretically based and shows that ET is directly related to the quantity of radiative energy gained by the exposed surface. In its simplified form, the Penman equation is[15]

$$ET = \frac{\Delta H + 0.27E}{\Delta + 0.27} \tag{5.27}$$

where Δ = the slope of the saturated vapor pressure curve of air at absolute temperature (mm Hg/°F)
H = the daily heat budget at the surface (estimate of net radiation) (mm/day)
E = daily evaporation (mm)
ET = the evapotranspiration or consumptive use for a given period (mm/day)

The variables E and H are calculated using the following equations:

$$E = 0.35(e_a - e_d)(1 + 0.0098u_2) \tag{5.28}$$

where e_a = the saturation vapor pressure at mean air temperature (mm Hg)
e_d = the saturation vapor pressure at mean dew point (actual vapor pressure in the air) (mm Hg)
u_2 = the mean wind speed at 2 m above the ground (mi/day)

The equation used to determine the daily heat budget at the surface, H, is

$$H = R(1 - r)(0.18 + 0.55S) - B(0.56 - 0.092e_d^{0.5})(0.10 + 0.90S) \tag{5.29}$$

where R = the mean monthly extraterrestrial radiation (mm H_2O evaporated per day)
r = the estimated percentage of reflecting surface
B = a temperature-dependent coefficient
S = the estimated ratio of actual duration of bright sunshine to maximum possible duration of bright sunshine.

The empirical reflective coefficient r is a function of the time of year, the calmness of the water surface, wind velocity, and water quality. Typical ranges for r are 0.05 to 0.12.[31] Values of e_a and Δ can be obtained from Figs. 5.7 and 5.8, those for R and B can be obtained from Tables 5.6 and 5.7. The use of Penman's equation requires a knowledge of vapor pressures, sunshine duration, net radiation, wind speed, and mean temperature. Unfortunately, regular measurements of these parameters are often unavailable at sites of concern and they must be estimated. Another complication is making a reduction in the value of ET when the calculations are for vegetated surfaces. While results of experiments to quantify reduction factors have not completely resolved the problem, there is evidence that the annual reduction factor is close to

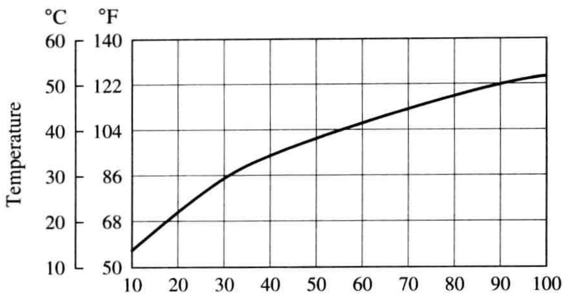

Figure 5.7 Relation between temperature and saturated vapor pressure.

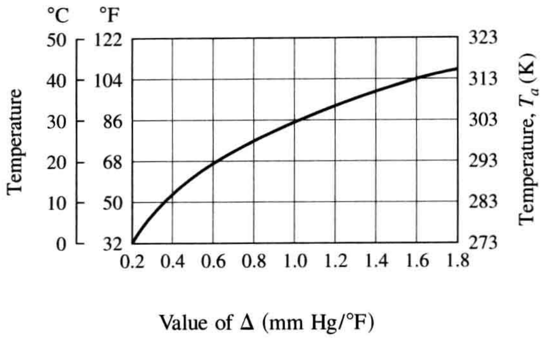

Figure 5.8 Temperature versus Δ relation for use with the Penman equation. (After Criddle.[23])

unity.[32–34] Thus, unless there is evidence to support another value, it appears that using a value of 1 for the reduction coefficient may give satisfactory results for surfaces having varied vegetal covers. Accordingly, any estimate of free water evaporation could be used to estimate *ET*, providing it is modified by an appropriate reduction coefficient.

EXAMPLE 5.4

Using the Penman Method, Eqs. 5.27 to 5.29, estimate *ET*, given the following data: temperature at water surface = 20 degrees C, temperature of air = 30 degrees C, relative humidity = 40 percent, wind velocity = 2 mph (48 mi/day), the month is June at latitude 30 degrees north, r is given as 0.07, and S is found to be 0.75.

Solution

1. Given the data for temperature, the values of e_a and e_d can be determined. Using Fig. 5.7 or Appendix Table A.2, the saturated vapor pressures are found to be 17.53 and 31.83 mm Hg respectively. Thus $e_a = 31.83$, and for a relative humidity of 40 percent, $e_d = 31.83 \times 0.4 = 12.73$.
   Then, using Eq. 5.28,

$$E = 0.35(31.83 - 12.73)(1 + 0.0098 \times 48)$$
$$E = 9.83 \text{ mm/day}$$

2. The value of Δ is found using Fig. 5.8; for the given latitude and month, R is obtained from Table 5.6; and B is gotten from Table 5.7 for a temperature of 30°C. The values found are $\Delta = 1.0$, $R = 16.5$, and $B = 17.01$.
   Then, using Eq. 5.29,

$$H = 16.5(1 - 0.07)(0.18 + 0.55 \times 0.75) - 17.01(0.56 - 0.092 \times 12.73^{0.5})(0.10 + 0.90 \times 0.75)$$
$$H = 6.04 \text{ mm/day}$$

TABLE 5.6 TABULATED VALUES OF *R*, MEAN MONTHLY INTENSITY OF SOLAR RADIATION ON A HORIZONTAL SURFACE,[a] FOR USE IN THE PENMAN EQUATION

	Latitude (deg)	J	F	M	A	M	J	J	A	S	O	N	D
North	60	1.3	3.5	6.8	11.1	14.6	16.5	15.7	12.7	8.5	4.7	1.9	0.9
	50	3.6	5.9	9.1	12.7	15.4	16.7	16.1	13.9	10.5	7.1	4.3	3.0
	40	6.0	8.3	11.0	13.9	15.9	16.7	16.3	14.8	12.2	9.3	6.7	5.5
	30	8.5	10.5	12.7	14.8	16.0	16.5	16.2	15.3	13.5	11.3	9.1	7.9
	20	10.8	12.3	13.9	15.2	15.7	15.8	15.7	15.3	14.4	12.9	11.2	10.3
	10	12.8	13.9	14.8	15.2	15.0	14.8	14.8	15.0	14.9	14.1	13.1	12.4
	0	14.5	15.0	15.2	14.7	13.9	13.4	13.5	14.2	14.9	15.0	14.6	14.3
South	10	15.8	15.7	15.1	13.8	12.4	11.6	11.9	13.0	14.4	15.3	15.7	15.8
	20	16.8	16.0	14.6	12.5	10.7	9.6	10.0	11.5	13.5	15.3	16.4	16.9
	30	17.3	15.8	13.6	10.8	8.7	7.4	7.8	9.6	12.1	14.8	16.7	17.6
	40	17.3	15.2	12.2	8.8	6.4	5.1	5.6	7.5	10.5	13.8	16.5	17.8
	50	17.1	14.1	10.5	6.6	4.1	2.8	3.3	5.2	8.5	12.5	16.0	17.8
	60	16.6	12.7	8.4	4.3	1.9	0.8	1.2	2.9	6.2	10.7	15.2	17.5

[a]Measured in mm H_2O evaporated per day.

Source: After Criddle.[23]