10.9

INFLUENCE OF CLIMATE ON SUBSURFACE DISPOSAL OF SEWAGE EFFLUENT[1]

10.9

C. B. Tanner and J. Bouma[2]

ABSTRACT

The main influences of climate on subsurface disposal of sewage effluent is on the water balance of the disposal field. The climate determines the maximum evapotranspiration (ET) losses and also the water that is added to the field by precipitation. There is a loss of effluent equal to the net difference between ET and precipitation; drainage must dispose of the remainder.

In the Great Lakes region, the net difference between ET and precipitation is totally inadequate for winter disposal of effluents from small-scale soil absorption disposal systems and is unreliable for summer. Even in arid regions the net ET cannot be relied upon for disposal in cold, low-radiation months. Therefore, sound design for disposal by drainage through the soil is mandatory.

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The disposal of sewage effluent, applied either to the surface or through a subsurface grid, is via drainage through the soil or via evapotranspiration (ET) from the surface. Since precipitation falling on the disposal field adds to the effluent volume, precipitation must be considered. Because both ET and precipitation mainly depend on climate, a simple way to formulate the disposal requirement is to determine the net difference between ET and precipitation; the effluent applied in excess of this net difference must be disposed of by drainage as indicated by

$$D = (V/A) - (ET - P)$$

where D, ET, and P are respectively the equivalent surface depths (e.g., cm) of drainage, evapotranspiration, and precipitation; V is the volume of effluent applied, A is the area of the disposal field, and (V/A) is the equivalent surface depth of effluent applied.

The drainage and ET from wet soil are not easily measured except with leak-free lysimeters, and would be very difficult to measure in a disposal field. However, estimates of the maximum ET can be made and this will indicate the importance of ET for effluent disposal relative to drainage through the soil. The disposal field needs to be designed to meet the drainage requirement reliably. Soil absorption of liquid waste can provide adequate on-site disposal and treatment of liquid waste; monitoring studies of the Small-Scale Waste Management Project at Wisconsin have shown that a wide range of soils are very effective for disposing and purifying domestic liquid waste, if the disposal system is properly designed and constructed.

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Evapotranspiration Estimates

Evapotranspiration depends on the supply of water at the evaporation surface (if there is no water there will be no ET) and on the weather; it depends on the weather because heat is required to change liquid water to vapor and the weather governs the amount of heat supplied. Since the soil and vegetation on the disposal field is always wet, ET depends primarily on the weather. The main source of heat is the solar radiation. However, if the disposal field is surrounded by dry land, heated air generated over the dry area travels with the wind to the wetter, and cooler, disposal field. This "advected" hot air can provide heat and increase ET.

Evapotranspiration also is influenced by the vegetation on the disposal field. Trees and bushes with a large silhouette catch more advected heat, similar to a clothesline. On the other hand, when vegetation is dormant, ET is much reduced. Snow cover influences the absorption of solar radiation, and when temperatures below freezing occur, more heat is required to change frozen water to vapor than liquid water. A final consideration is the heat carried to the disposal field by the effluent and the heat generated by biological activity in the field.

We will first estimate the maximum ET under nonadvective conditions. We then will consider how this would be modified by snow and low temperatures, by advection, by the vegetation cover (tall form trees or bushes and dormant vegetation), by the heat in the effluent, and by biologically generated heat.

Maximum ET, nonadvective conditions: Priestley and Taylor[14/] describe a simple method of estimating ET from well-watered surfaces that works well when there is no advected heat. This method, which is detailed in the appendix, is suited to the Great Lakes region, and has been confirmed by us and others.

In Table 1, we give the calculated maximum ET from a grass surface at Madison, based on mean climate data for 20 years. We have assumed that the grass is never dormant in winter and is never short of water; this will give over-estimates of ET in the winter months. The estimates of ET for the warm months are slightly larger than lysimeter measurements made at Hancock, Wisconsin. Also because this estimate takes no account of heat flow into the soil in the spring and out of the soil in the fall, spring values are somewhat too large and fall values are too low; however, this does not affect the main results.

Table 1. Maximum ET; precipitation, P; and ET - P for Madison, Wisconsin.

Month	ET cm	P cm	ET - P cm	Month	ET cm	P cm	ET - P cm
May	11.9	8.7	3.2	Nov.	0.9	4.7	-3.8
June	14.9	11.0	3.9	Dec.	0.5	3.7	-3.2
July	16.3	9.7	6.6	Jan.	1.3	3.2	-1.9
Aug.	13.4	7.7	5.7	Feb.	2.4	2.4	0.0
Sept.	7.8	8.4	-0.6	March	4.5	4.9	-0.4
Oct.	3.7	5.5	-1.8	April	7.4	6.8	0.6
Total	68.0	51.0	17.0	Total	17.0	25.7	-8.7

By way of comparison, an effluent volume of 1 cubic meter/day (264 gal/day) disposed on 200 square meters (2,150 sq. ft.) is equivalent to 5 mm/day or about 15 cm/month. This is much in excess of the (ET - P) for any month, indicating that effluent disposal must rely heavily on drainage.

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We can compare the ET calculated in Table 1 with some other regions for which lysimeter data are available[9]. These data, shown in Fig. 1, are for well-watered grass and alfalfa. The ET at Coshocton is similar to that calculated for Madison, but is somewhat greater, as would be expected for the lower latitude. ET is extreme for Brawley in the Imperial Valley, where solar radiation is great and advection occurs. Since there is little precipitation, ET could dispose of the effluent in the above example (1 m^3/day on 200 m^2) for about six months of the year. At Davis, a Mediterranean climate, ET is substantially less than at Brawley, but the ET could dispose of the effluent for 4 months of the year (there is little precipitation at Davis during these months).

Even with the extreme ET, such as at Brawley, drainage is essential to dispose of effluent for several months of the year.

Effect of snow and freezing temperature: Snow cover reflects much more radiation than does green grass so there will be less ET. If the disposal field is covered with snow, there will be minor sublimation of the snow surface but the snow shields the surface preventing a net loss of evaporation from the disposal field. Also at these low temperatures a unit of sunlight produces less ET. For example, our calculations for an active grass surface above freezing indicate a 17-cm ET from November through April. Lysimeter measurements at Hancock, Wisconsin indicate the ET during this period is 5 cm or less.

Advection: Advection can double the ET from a small irrigated grass plot (230 m^2) when the surrounds are very dry[16]. However, this is extreme for arid regions, and in humid regions advection is neither frequent nor large, seldom exceeding 25%.

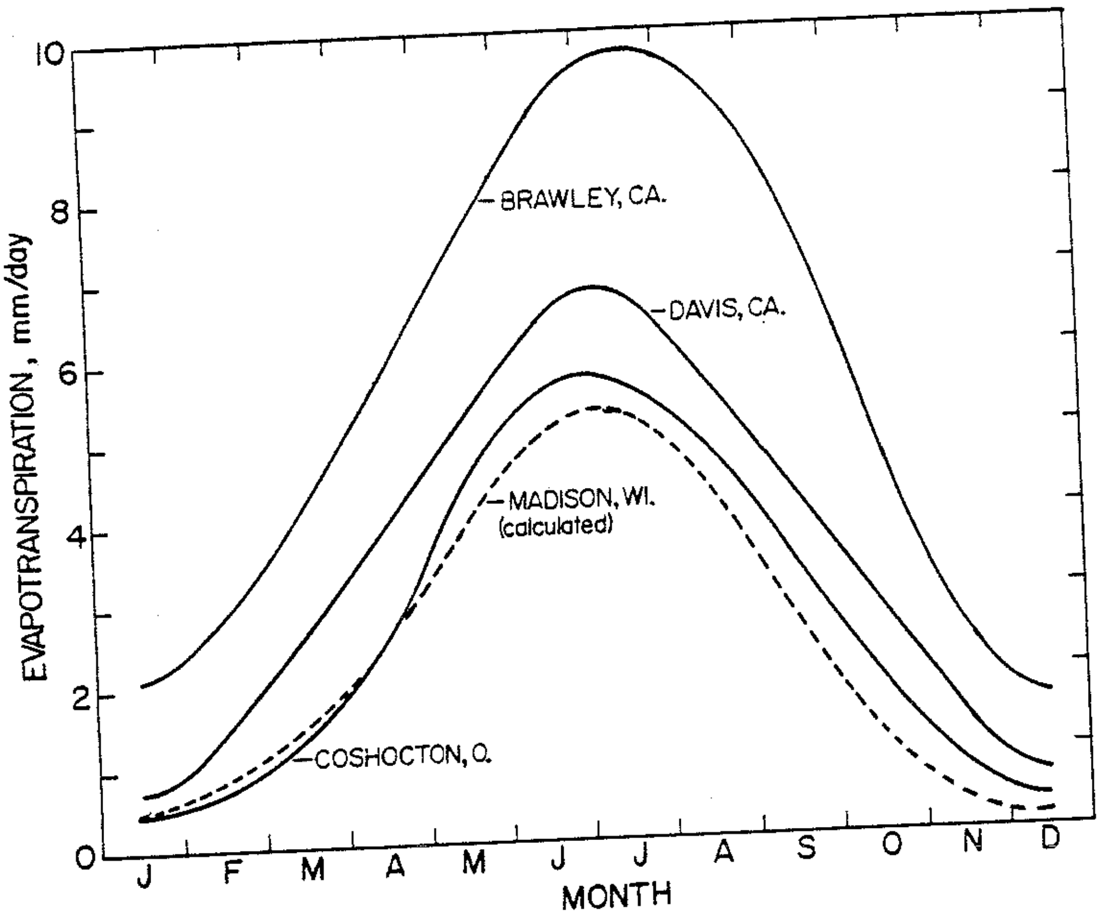
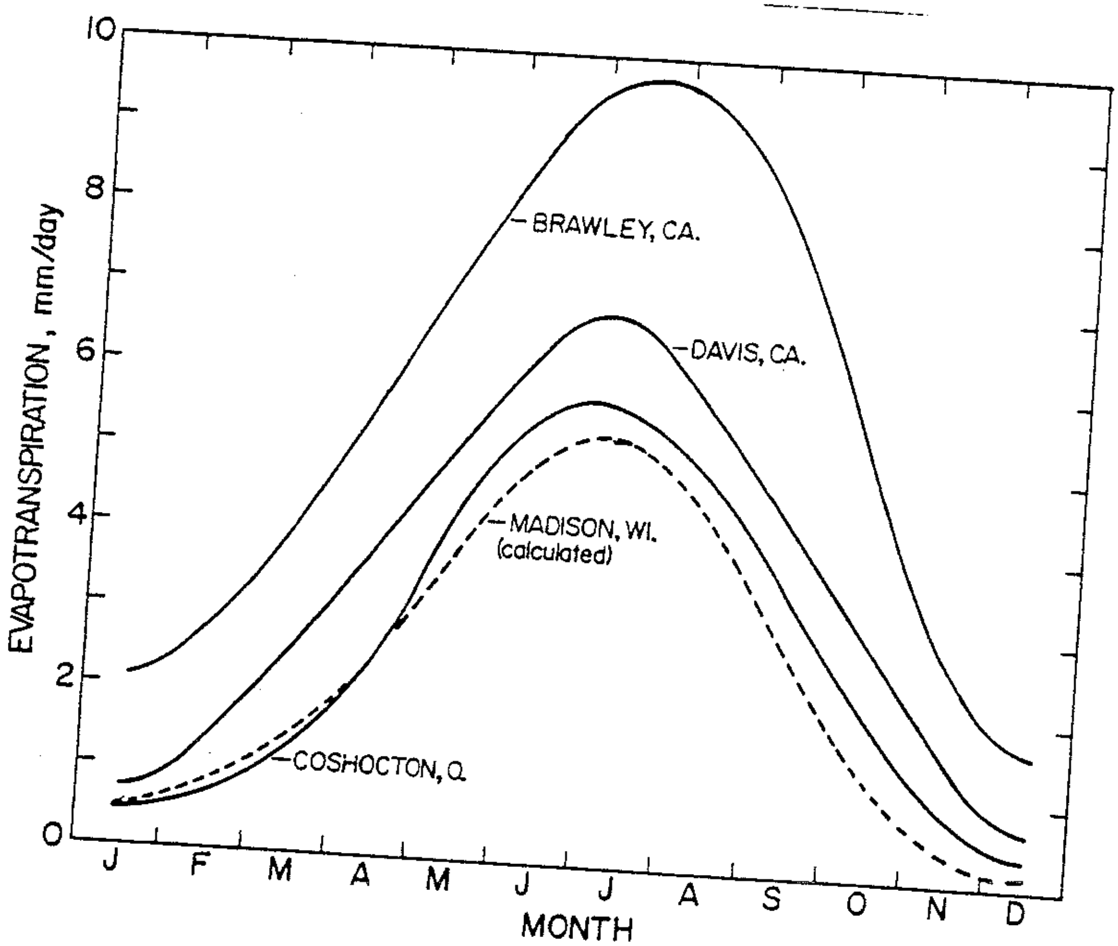


Fig. 1. Evapotranspiration from well-watered grass and alfalfa in lysimeters at different locations in the United States (from Jensen[9]).



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Effect of vegetation: Grass, flowers, and deciduous shrubs that become dormant during winter do not transpire. In absence of snow, this dormant vegetation shields the surface from radiant and advected heat and decreases transpiration. Taller vegetation also catches snow, thus providing further ET shielding.

Trees and shrubs present a silhouette to the wind and the advection increases the ET (the clothesline effect). The ET from evergreen shrubs and trees may exceed deciduous trees in winter[15/]. There are few data on the ET of isolated trees, except for small seedlings, and only crude estimates can be made. Some data on the transpiration of trees is given in Table 2.

Table 2. Transpiration from evergreens.

Source	Species	Height (m)	Season	T m^3/day
Minckler[11/]	White pine	9.8	Summer	0.0057
Minckler[11/]	White pine	13.7	Summer	0.0057
Minckler[11/]	White pine	17.7	Summer	0.025
Parker[12/]	White pine	14.0	Summer	0.18
Fritschen & Doraiswamy[6/]	Douglas fir	28.0	Spring	0.05
Waggoner[17/]	Jack pine	2.0	Summer	0.002

Parker's and Minckler's values are estimates based on water loss of detached shoots, and may be questioned. The last two are lysimeter measurements and are more reliable. Provided the stomata do not change, the transpiration would vary proportionately with the saturation deficit[4/]. Saturation deficits can be approximated for these calculations as the difference in the saturation vapor pressures corresponding to maximum and minimum temperatures[7/]. Vapor pressures in millibars (mb) for different temperatures are given in Table A1. From saturation deficit data at the two sites, we find that the large Douglas fir would transpire 4 liters day^{-1} mb^{-1}, and the Jack pine would transpire 0.2 liter $day^{-1}mb^{-1}$. At Madison and Coshocton the summer transpiration would be about the same as in Table 2, but at Brawley, with a large saturation deficit, it would be 4-fold.

If the 2-meter high trees were planted on 2 meter centers over a disposal field at Madison they would increase the ET during the summer only 20%. During cold winters, transpiration would meet only a small part of the requirement because the saturation deficit is small and the stomata are nearly closed at freezing temperatures[5/]. Using larger trees would not offer any advantage because fewer could be planted on the disposal field. Additionally, planting trees on the disposal field is a questionable practice because roots will enter the gravelbed and grow into and around the distribution system, thereby impairing it. A row of trees could be planted around the system when a seepage bed is constructed or rows of trees could be planted in soil separating seepage trenches. However, the above calculations clearly indicate that the additional transpiration from evergreens does not justify risking damage to the distribution system.

Effluent heat: We will make a calculation of the maximum ET that would result from one cubic meter (264 gal) of effluent added to the disposal field at 25°C (77°F), assuming that the effluent is chilled to 0°C (32°F) and that all the heat given up goes into evaporation. This would give an extreme evaporation since all the heat will not go into evaporation, and disposal fields must operate above freezing. The heat given up would be about 10^8 joules (100,000 BTU or 25,000 kcal). Since 2.5 million joules are required to evaporate a liter, about 42 liters (0.042 m^3 = 11 gal) would be evaporated. Thus, the heat in the effluent would evaporate less than 5% of the total effluent.

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Biological heat production: Oxidation of effluent generates energy in the form of heat which could contribute to increased evaporation. Bernhardt[2] distinguishes between "aerobic" systems (page 30, Figure 2-14) and "anaerobic" systems (Figure 2-12), but his distinctions are not clear since in both systems "the lower parts of the trenches are frequently inundated." This unclear distinction is related to the statement that "microbial energy increases the evaporation rate" (page 143). Since energy released from anaerobic decomposition is an order of magnitude lower than from aerobic (R. F. Harris, U.W. soil bacteriologist, personal communication), we can calculate the heat generated for aerobic systems as a maximum.

Two approaches can be taken to solve this question. (a) Septic tank effluent has COD of approximately 250 mg/liter. Daily production for a family of four is approximately 1,000 liters (1 m^3 = 264 gal). Total production is then "250 grams COD" which is equivalent to 180 grams of volatile solids[18]. Since there is a generation of 5.46 kcal of heat energy per gram of (organic) solids[13], a heat energy yield of 983 kcal is obtained. Evaporation of one liter of water requires 600 kcal, so we can evaporate approximately 1.64 liters of water per day. (b) Following standard techniques, we use in some of our column experiments, a solution of 100 mg/liter dextrose and 100 mg/liter glutamic acid to simulate the COD of septic tank effluent. Energy yields of complete aerobic oxidation can be calculated from heats of combustion in the Chemistry Handbook:

1 mole dextrose yields 673 kcal or 673/180 = 3.9 kcal/g

1 mole glutamic acid yields 514 kcal or 514/132 = 3.9 kcal/g

A daily production of 1,000 liters of the simulated "effluent" contains 100 g dextrose and 100 g glutamic acid, which represent a total potential heat release of 780 kcal. This would evaporate 1.3 liter of water, comparable with the first calculation above.

Our estimates of heat production from aerobic decomposition indicate less than 0.2% of the effluent would be evaporated from this source of heat. Anaerobic decomposition would produce even less ET. If our estimates are within a factor of ten, biological decomposition is irrelevant to effluent ET.

Summary

Evapotranspiration processes can theoretically remove significant volumes of effluent from subsurface disposal systems in late spring, summer and early fall, particularly if high-silhouette, good transpiring bushes and trees are present. However, the effectiveness of ET for on-site effluent disposal is determined by the difference between ET and precipitation -- the net ET loss. In humid regions the net ET loss is inadequate for disposal of effluent from a typical household without using inconveniently large disposal areas.

The decrease of ET in winter at middle- and high-latitudes greatly limits ET for winter disposal; under freezing conditions ET would be totally inadequate.

Soil disposal systems which should work all year long under Wisconsin conditions, cannot be designed exclusively on the basis of evapotranspiration removing the liquid waste, nor can this be the design basis for other regions in the United States, particularly those high-latitude, cool-winter locations. Soil absorption of liquid waste remains the only viable means for providing adequate on-site disposal and treatment. This conclusion is quite acceptable because monitoring studies of the Small Scale Waste Management Project have shown that a wide range of soils are very effective as purifiers of domestic liquid waste, if the disposal system is properly designed and constructed.

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APPENDIX

We will outline here, a simple procedure for estimating the maximum ET from disposal fields for the nonadvective conditions such as found in the United States east of the Mississippi. Lysimeter data and more complicated procedures outlined in Jensen[9] can be used for advective arid and semi-arid conditions.

Drainage is difficult to measure or estimate but can be inferred by measuring the change of soil water in a disposal field with a neutron meter following cessation of effluent input. The disposal field must be covered completely with plastic sheets topped with a heavy straw mulch to prevent ET. The drainage often is a function of the water content[3,10].

Evapotranspiration formula: We, and many others, have found the method of Priestley and Taylor[14] works very well for estimating maximum ET over water surfaces, wet soil, and vegetation that transpires well (many open stomata), provided temperatures are above freezing and that there is no advection. The estimate is:

$$ET_{max} = 1.28[s/(s+\gamma)]\ R_n$$

where s is the slope of the saturation vapor pressure curve corresponding to ambient air temperature; γ is the psychrometer constant (same units as s); and R_n is the net radiation in evaporation units of mm/day. Values of $[s/(s+\gamma)]$ are given in Table A1 for different temperatures.

Net radiation: The R_n can be found from the daily solar radiation and temperature as:

$$R_n = (1 - r)R_G - R_{Tn}$$

Table A1. Values at different temperatures of [s/(s+γ)] for sea level and 1,650 meters (5,000 ft) elevation, σT^4, and vapor pressure.

Temp. °C	s/(s+γ) Sea Level	s/(s+γ) 1,650 m	σT^4 mm/day	Vapor Pressure mb 1\
-30	0.058	0.068	6.10	0.38
-20	0.133	0.153	7.16	1.03
-10	0.261	0.294	8.36	2.58
0	0.406	0.446	11.02	6.11
5	0.482	0.523	11.90	8.72
10	0.555	0.595	12.83	12.27
15	0.623	0.660	13.82	17.04
20	0.684	0.717	14.87	23.37
25	0.737	0.766	15.98	31.67
30	0.782	0.807	17.15	42.43
35	0.819	0.841	18.40	56.24
40	0.851	0.869	19.71	73.78

1\ Interpolate from log mb vs. temperature.

where R_G is the solar radiation, r is the albedo (reflectance) of solar radiation by the surface and R_{Tn} is the net long-wave, thermal radiation loss.

R_G is available from weather records; however, it usually is in units of cal $cm^{-2} day^{-1}$ or Langley/day (1 Ly = 1 cal/cm^2). To convert to evaporation units of mm/day we use the conversion of 1 mm = 67.5 cal/cm^2 when temperature is below freezing and 1 mm = (59.5 - 0.05 T_C) cal/cm^2 above freezing; for example at 10°C 1 mm = 59 cal/cm^2.

We will use an albedo r = 0.2. Although the albedo of many vegetation surfaces is higher than 0.2, using this value will overestimate ET. The albedo of snow is 0.6 or more.

The net thermal radiation loss, R_{Tn} is calculated in two steps. We first calculate R_{Tn}(clear) for clear skies according to the formula of Idso and Jackson[8/].

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$$R_{Tn}(\text{clear}) = (\sigma T^4)[0.261 \exp(-7.77 \times 10^{-4} T_C{}^2]$$

This formula requires mean air temperature in degrees Celsius, T_C, and the black body radiation, σT^4, corresponding to the absolute temperature, T; σT^4 is given in Table A1.

Clouds attenuate the loss of thermal radiation and so a correction of R_{Tn}(clear), as found above, is needed to account for cloudiness and give R_{Tn}. The simplest correction is

$$R_{Tn} = [R_{Tn}(\text{clear})][R_G/R_G(\text{clear})]$$

This correction is fairly good and any error results in slight underestimates of R_{Tn} and overestimates of ET.

Example calculation: We will go through calculations of ET for July as an illustration. Base data for Madison are given in Table A2. The solar radiation data are from Baker and Klink[1/], and also are available from the U. S. Department of Commerce, National Climate Center, Federal Building, Ashville, NC, 28801.

Table A2. Climate data for Madison, Wisconsin.

Month	Solar radiation, cal $cm^{-2} day^{-1}$ Mean	Clear day	Temp. ^oC
J	171	297	-8.1
F	246	418	-6.9
M	339	588	-1.6
A	408	723	6.7
M	505	820	13.4
J	562	861	18.9
J	561	841	21.7
A	498	728	20.8
S	379	582	16.1
O	256	442	9.9
N	151	300	1.1
D	122	242	-5.5

The major calculation is to find R_n. To do this, we first find R_{Tn}(clear). We have for July

$$R_{Tn}(\text{clear}) = (15.2 \text{ mm/day})(0.261)\exp[-(0.000777)(21.7)^2]$$
$$= (3.97 \text{ mm/day})\exp(-0.366) = 2.75 \text{ mm/day}$$

Then using R_G/R_G(clear), we find R_{Tn}

$$R_{Tn} = (2.75 \text{ mm/day})(561/841) = 1.83 \text{ mm/day}$$

In order to get $R_n = (1-r)R_G - R_{Tn}$, we first convert R_G from (cal/cm^2)/day to mm/day. In July, 1 mm = 59.5 − (0.05)(21.7°C) = 58.4 cal/cm², and

$$R_G = 561(\text{cal/cm}^2)/\text{day} = (561/58.4)\text{mm/day} = 9.61 \text{ mm/day}$$

Then R_n is found as

$$R_n = (1-0.2)(9.61 \text{ mm/day}) - 1.83 \text{ mm/day} = 5.86 \text{ mm/day}$$

Having found R_n, we then find the ET.

$$ET = (1.28)(0.700)(5.86 \text{ mm/day}) = 5.25 \text{ mm/day}$$

Multiplying by days in the month gives the data for Madison in Table A1; ET for other months was found similarly, except that $[s/(s+\gamma)] = 0.406$ was used to ensure highest estimates of winter ET.

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$$R_G = 561(\text{cal/cm}^2)/\text{day} = (561/58.4)\text{mm/day} = 9.61 \text{ mm/day}$$

Then R_n is found as

$$R_n = (1-0.2)(9.61 \text{ mm/day}) - 1.83 \text{ mm/day} = 5.86 \text{ mm/day}$$

Having found R_n, we then find the ET.

$$ET = (1.28)(0.700)(5.86 \text{ mm/day}) = 5.25 \text{ mm/day}$$

Multiplying by days in the month gives the data for Madison in Table A1; ET for other months was found similarly, except that $[s/(s+\gamma)] = 0.406$ was used to ensure highest estimates of winter ET.

We note that the ET in the winter months is overestimated by assuming the grass is green and viable with low reflectance and transpires as if the temperature were close to $0^{\circ}C$ but not freezing (we use $[s/(s+\gamma)] = 0.406$).

References

1. Baker, D. G. and J. C. Klink. 1975. Solar radiation reception, probabilities and areal distribution in the North Central region. Univ. Minnesota Agric. Exp. Sta. Tech. Bull. No. 300. 54 p.

2. Bernhardt, A. P. 1973. Treatment and Disposal of Waste Water from Homes by Soil Infiltration and Evapo-transpiration. Toronto, Canada.

3. Black, T. A., W. R. Gardner, and C. B. Tanner. 1970. Water storage and drainage under a row crop on a sandy soil. Agron. J. 62: 48-51.

4. Black, T. A. and C. S. Tan. 1975. Factors affecting the canopy resistance of a Douglas-fir forest canopy. Presented Ninth Ann. Canadian Meteorological Soc. Congr., 27-30 May, Vancouver.

5. Christersson, L. 1972. The transpiration rate of unhardened, hardened, and dehardened seedlings of spruce and pine. Physiologia Pl. 25: 258-263.

6. Fritschen, L. J. and P. Doraiswamy. 1973. Dew: an addition to the hydrologic balance of Douglas fir. Water Resources Res. 9: 891-894.

7. Gentilli, J. 1955. Estimating dew point from minimum temperature. Bull. Amer. Meteorol. Soc. 36: 128-131.

8. Idso, S. B. and R. D. Jackson. 1969. Thermal radiation from the atmosphere. J. Geophys. Res. 74: 5397-5403.

9. Jensen, M. E. 1974. Consumptive use of water and irrigation water requirements. Amer. Soc. Civil Engr., New York. 215 p.

10. Miller, D. E. and J. S. Aarstad. 1972. Estimating deep drainage between irrigations. Soil Sci. Soc. Amer. Proc. 36: 124-127.

11. Minckler, L. S. 1939. Transpiration of trees and forests. J. For. 37: 336-339.

12. Parker, J. 1957. The cut leaf method and estimations of diurnal trends in transpiration from different heights and sides of an oak and a pine. Bot. Gaz. 19: 93-101.

References

1. Baker, D. G. and J. C. Klink. 1975. Solar radiation reception, probabilities and areal distribution in the North Central region. Univ. Minnesota Agric. Exp. Sta. Tech. Bull. No. 300. 54 p.

2. Bernhardt, A. P. 1973. Treatment and Disposal of Waste Water from Homes by Soil Infiltration and Evapotranspiration. Toronto, Canada.

3. Black, T. A., W. R. Gardner, and C. B. Tanner. 1970. Water storage and drainage under a row crop on a sandy soil. Agron. J. 62: 48-51.

4. Black, T. A. and C. S. Tan. 1975. Factors affecting the canopy resistance of a Douglas-fir forest canopy. Presented Ninth Ann. Canadian Meteorological Soc. Congr., 27-30 May, Vancouver.

5. Christersson, L. 1972. The transpiration rate of unhardened, hardened, and dehardened seedlings of spruce and pine. Physiologia Pl. 25: 258-263.

6. Fritschen, L. J. and P. Doraiswamy. 1973. Dew: an addition to the hydrologic balance of Douglas fir. Water Resources Res. 9: 891-894.

7. Gentilli, J. 1955. Estimating dew point from minimum temperature. Bull. Amer. Meteorol. Soc. 36: 128-131.

8. Idso, S. B. and R. D. Jackson. 1969. Thermal radiation from the atmosphere. J. Geophys. Res. 74: 5397-5403.

9. Jensen, M. E. 1974. Consumptive use of water and irrigation water requirements. Amer. Soc. Civil Engr., New York. 215 p.

10. Miller, D. E. and J. S. Aarstad. 1972. Estimating deep drainage between irrigations. Soil Sci. Soc. Amer. Proc. 36: 124-127.

11. Minckler, L. S. 1939. Transpiration of trees and forests. J. For. 37: 336-339.

12. Parker, J. 1957. The cut leaf method and estimations of diurnal trends in transpiration from different heights and sides of an oak and a pine. Bot. Gaz. 19: 93-101.

13. Payne, W. J. 1973. Bacterial growth yields, p. 57-93. In Buarria, L. J. and R. K. Ballentine [eds.] The aquatic environment. EPA 430/G-73-008, Washington, D. C.

14. Priestley, C. H. B. and R. J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Rev. 100: 81-92.

15. Rutter, A. J. 1968. Water consumption by forests, p. 23-84. In Kozlowski, T. T. [ed.] Water deficits and plant growth: plant water consumption and response. Academic Press, N.Y.

16. Tanner, C. B. and E. R. Lemon. 1962. Radiant energy utilized in evapotranspiration. Agron. J. 54: 207-212.

17. Waggoner, P. E. 1967. Transpiration of trees and chemicals that close stomata, p. 483-489. In Sopper, W. E. and H. W. Lull [eds.] Forest hydrology. Pergamon Press, Oxford.

18. Young, J. C. and P. L. McCarty. 1969. The anaerobic filter for waste treatment. J. Water Poll. Contr. Fed. 41(5): R160-R173.

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