EVAPOTRANSPIRATION FROM TWO PEATLAND WATERSHEDS

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SUMMARY

Measurements of precipitation, runoff, and bog water table levels have provided data for the calculation of evapotranspiration from two forested peatland watersheds near Grand Rapids, Minnesota (ca. 47° 32′N, 93° 28′W). Continuous hydrologic records were collected on one experimental bog for 6 years (1961-1966) and on the other for the past 2 years (1965-1966). Water level changes in each bog were converted to inches-depth of storage by water yield coefficients for specific peat horizons and used to adjust precipitation-runoff calculations.

Evapotranspiration estimates for the growing-season period May 1 to November 1 ranged from 87 to 121 percent of potential evapotranspiration computed by the Thornthwaite method. Midsummer evapotranspiration totals (June 1 to September 1) were 70 to 99 percent of potential evapotranspiration. Mean daily evapotranspiration values from both bogs during short summer drying periods were consistently less than the calculated potential values.

RÉSUMÉ

Les mesures des précipitations, écoulement et niveaux des nappes aquifères de tourbières ont fourni des données pour le calcul de l'évapotranspiration de deux tourbières boisées près de Grand Rapids, Minnesota (ca. 47° 32′N, 93° 28′O). Des renseignements hydrologiques ont été recueillis continuellement pendant 6 ans dans une tourbière expérimentale (1961-1966) et dans une autre les deux dernières années. Les variations de niveau d'eau de chaque tourbière ont été exprimées en «pouces-profondeur» d'eau accumulée en tenant compte d'un coefficient de correction d'eau, spécifique à chaque tourbière; ces mesures ont été utilisées pour mettre au point le calcul des précipitations et écoulements.

Les estimations d'évapotranspiration faites pour la saison de croissance allant du 1er mai au 1er novembre varient de 87 à 121% de l'évapotranspiration potentielle calculée par la méthode Thornwaite. Les totaux de l'évapotranspiration au cours de l'été (du 1er juin au 1er septembre) varient de 70 à 99% de l'évapotranspiration potentielle calculée. L'évapotranspiration quotidienne moyenne des deux tourbières pendant les courtes périodes de sécheresse estivale était substantiellement inférieure aux valeurs potentielles calculées.

Peatlands cover large areas in the northern and boreal forests of the north central United States. These saturated lands form the watersheds for the headwaters of a number of important rivers, yet little is known about their water economy. Because they have high water tables, evapotranspiration from such undisturbed areas might be expected to approach potential evapotranspiration for a given climatic area; and some studies have shown that actual and potential evapotranspiration are similar under optimal conditions (Eggelsmann 1963). Evidence is available, however, that evapotranspiration varies in different types of bogs (Romanov 1961) and for various forest communities (Molchanov 1960). Much more needs to be known about the influence of vegetation management and water control practices on the water economy of peatland watersheds.

Evapotranspiration from peatlands has been studied in northern Europe and the Soviet Union (Virta 1966), but few detailed studies in the northern United States have

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been reported. At present, however, the hydrology of peatland watersheds is being investigated in northern Minnesota near Grand Rapids (ca. 47° 32′ N, 93° 28′ W). For the first time in the United States, detailed measurements of precipitation, runoff, bog water table levels, and the local groundwater hydrology are being collected on forested peatland watersheds. Measurements on water storage changes within a bog and knowledge of its hydrogeologic situation have helped to make possible the calculation of evapotranspiration by the water balance method. Such data are not usually available on study watersheds.

This paper explains the use of the water balance method on two study bogs and compares seasonal and short-term estimates with potential evapotranspiration as computed by the Thornthwaite method.

THE STUDY WATERSHEDS

The two watersheds selected for this study, *S*-2 and *S*-6, are only 24 and 22 acres (9.7 and 8.9 hectares) in size, respectively. Each contains a filled-lake-type peat bog, covering 8 acres (3.2 hectares) in *S*-2 (fig. 1) and 5 acres (2 hectares) in S-6. The bogs appear to have been formed in ice-block depressions within a terminal moraine complex. Depth of peat within the bogs varies from a few feet at the margins to 28 feet (less than a meter to about 8.5 meters) in the deepest portions. Peat types near the surface are fairly similar in both bogs.

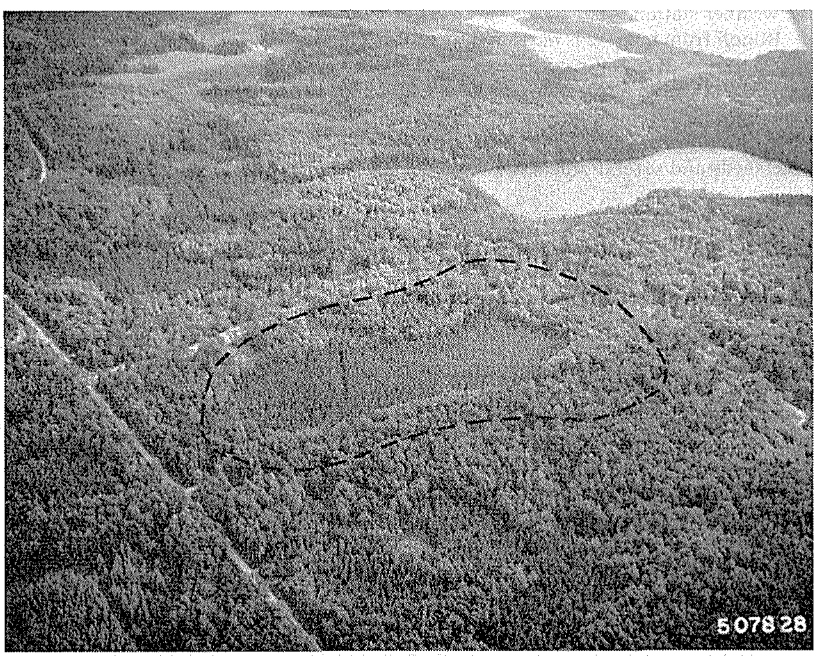

Fig. 1 — Air photo of bog S-2 (in center of photo). Approximate watershed boundary shown as broken line.

Geologically the area is considered an over-ridden moraine, with a thin veneer of clay-loam till covering deep sands. On the watersheds, the till cap averages about 8 to 12 feet thick (2.4 to 3.6 m). Hydrogeologic investigations have located a local groundwater system below the bog basins. The bogs are thus perched above, and separated from the underground flow system. There should be little, if any, deep seepage from the bogs to the underground system. This assumption is supported by measurements of the deep water table which show (1) no correlation between bog water table levels and fluctuations in underground basin storage, and (2) very little recession of the bog water tables in the winter, when there is no surface runoff or evapotranspiration.

The vegetation is similar on both watersheds and is representative of forested peatlands in similar geologic situations throughout the northern Lake States. The upland mineral soil areas support almost pure stands of quaking aspen (*Populus tremuloides*) with a dense understory of beaked filbert (*Corylus cornuta*). Both bogs support almost pure stands of black spruce (*Picea mariana*), although the spruce is somewhat less dense on bog *S*-6. The understory vegetation on the bogs is primarily heath shrubs: *Chamaedaphne calyculata* var. *angustifolia*, *Ledum groenlandicum*, *Andromeda glaucophylla*, and *Gaultheria hispidula*. The bog surface is covered with *Sphagnum* spp. and other mosses and moss-like plants such as *Calliergonella schreberi* and *Polytricum juniperinum*.

Both bogs were instrumented in a similar manner, beginning in 1960 on *S*-2 and 1964 on *S*-6. Precipitation is collected in two U.S. Weather Bureau standard rain gages on each watershed and in a recording rain gage located at a weather station on watershed *S*-2. The weather station also contains a hygrothermograph and maximum and minimum thermometers. Watershed *S*-6 is located 1/4 mile (ca. 0.4 km) away from the weather station.

Runoff from bog *S*-2 is measured by a 120° V-notch weir located at the outlet of the bog. Continuous runoff records are collected at bog *S*-6 by a 1.5-foot (.46 m) type "H" flume. Water table fluctuations within each bog are measured by water level recorders in permanent well installations.

A complete discussion of the instrumentation and research techniques for these watersheds and several others in the immediate vicinity is given by Bay (1967).

Computation of Water Balance

The basic theory of estimating evapotranspiration (*ET*) by the water balance method is fairly simple, but the reliability of results is often questionable because errors in measuring any component of the water balance equation are directly reflected in the *ET* term. Basically the equation is:

$$ET = P - R + I - S - U \qquad (1)$$

where

P precipitation on the watershed;
R runoff which leaves the watershed;
I inflow to the watershed;
S change in soil moisture storage;
U deep seepage from the watershed.

For the watersheds under study, precipitation and runoff were measured directly. Average watershed precipitation was determined by the Thiessen method (Linsley *et al.* 1949). Runoff at the stream gages was converted to area inches, using total watershed areas—that is, the total surface area (both bog and uplands) contributing water to the runoff gage. The accuracy of the runoff data depends greatly upon the precision with which watershed boundaries can be drawn in this morainal topography. A contour map with 4-foot (1-1/4 m) intervals was available to aid in selecting the contributing area, and these two particular watersheds were selected from all the study watersheds because they were relatively easy to define. In addition, they receive no inflow from other bogs or streams; thus, the inflow term is not applicable in this situation.

As discussed earlier, seepage to the underground basin from the bogs is considered to be negligible. Also deep percolation from the mineral soil uplands is assumed to be small during the evaporative season for two reasons: Rainfall patterns and data from similar soils indicate that soils are seldom fully recharged at that time; and the cap of fine-textured glacial till restricts downward movement of water.

Changes in soil water storage on the upland soils were not directly measured. In the region of the study, soils are normally recharged by late April or early May soon after snowmelt. Active vegetation development does not begin until approximately mid-May. Soil moisture recharge begins again in September and October and continues until snowfall in November. There could be some differences in soil moisture storage for shorter intervals of time depending upon precipitation depth and distribution in spring and fall. However, on a long-term basis, differences in soil moisture between spring and late fall are considered to be small.

Within the peatlands, differences in water storage between the beginning and end of specified periods of time were computed from records of the recording wells. Differences in water stages in the bogs were converted to actual inches of water storage by water yield coefficients determined for various horizons within the peat profile. Virta (1966) and Vorob'ev (1963) have discussed several ways of determining such water yield coefficients. In this study, the coefficients were determined by computing the regression coefficient between water level changes and precipitation for selected short-duration storms when the water table was located at specific elevations in the peat profile. This is similar to the method described by Vorob'ev (1963). The values obtained for bog *S*-2 were checked by two additional independent measures of the water yield coefficient.

In one independent test, coefficients were determined for the upper peat horizons from pumping tests conducted in evapotranspirometers similar to those described by Bay (1966). Another set of coefficients was determined from laboratory data and decribed in part by Boelter (1964). The three sets of water yield coefficients are shown in table 1 and support the use of precipitation-water level fluctuation data.

TABLE 1

Water yield coefficients for several peat horizons in bog S-2

Depth from average surface (ft)	Bulk density(1) (g/cc)	Water yield coefficients(2)		
		Y_1	Y_2	Y_3
0— .70	.02	0.67	0.67	0.79
.70— .90	.05—.06	0.52	0.50	0.52
.90—1.25	.06—.08	0.29	—	0.28

(1) Saturated volume basis.
(2) Determined by the three methods discussed in text:
Y_1 precipitation vs. water level change;
Y_2 pumping test in evapotranspirometers;
Y_3 laboratory-determined value (supplied by Dr. D.H. Boelter).

The above data and assumptions than reduce equation (1) to:

$$ET = P - R - S_b \qquad (2)$$

where

S_b change in water storage within the bog.

This equation was used to estimate *ET* from the watersheds.

Seasonal and Short-Term Evapotranspiration

For comparison purposes, potential *ET* was calculated by the Thornthwaite method from monthly and periodic mean air temperatures collected at the nearby weather station (Thornthwaite and Mather 1957). Estimates of *ET* from water balance data for May 1 to November 1 during 6 years varied from 88 to 116 percent of computed potential *ET* on *S*-2 watershed and were 98 and 121 percent of potential for the 2 years measured on watershed *S*-6 (table 2).

In half the years, *ET* estimated by the water balance method closely approached potential *ET*. The large difference in 1961 may have been due to a very warm and dry summer when bog water tables reached record lows. Available moisture was probably limited and hence limited actual *ET*, whereas the higher temperatures increase the calculated potential *ET*. Similarly, high temperatures in the fall of 1963 probably inflated potential values for that year, while extremely low rainfall and lack of leaves on the deciduous vegetation probably limited actual evaporative loss.

A different situation prevailed in 1965 when *ET*'s computed by the water balance method were considerably higher than potential *ET*'s for both bogs. Three times the normal September rainfall may have resulted in deep percolation through the upland areas to the underground basins below the watersheds. Graphs of deep water table levels showed an increase in basin storage in October and November of that year.

TABLE 2

Seasonal evapotranspiration estimates from water balance data and potential evapotranspiration, May 1 to November 1 (in inches)(1)

Bog and year	*P*	*R*	S_b	*ET*	Potential *ET*
S-2					
1961(2)	20.19	3.50	−2.12	18.81	21.16
1962	22.76	5.98	−2.81	19.59	19.23
1963	20.05	3.18	−1.44	18.31	20.76
1964	23.51	6.49	−2.39	19.41	20.67
1965	22.78	5.19	−2.60	20.19	17.46
1966	22.53	5.55	−2.94	19.92	20.11
S-6					
1965	22.63	4.11	−2.20	20.72	17.09
1966	21.44	5.26	−3.51	19.69	20.11

(1) See Equations 1 and 2 for explanation of symbols in column headings.
(2) Measurements in 1961 did not begin until May 10 because of ice in the recording well. All computations were adjusted to this data.

Potential *ET*'s, on the other hand, are the lowest on record because exceptionally low minimum temperatures for several days in August and September lowered average periodic temperature.

The results for these 3 years illustrate inherent problems in calculating *ET* and potential *ET* that accentuate the differences between them.

Mid-summer water balance values were somewhat lower than potential *ET* for each year (table 3). The values varied from 70 to 94 percent of potential *ET* on watershed *S*-2 but were much closer on *S*-6, approximately 96 and 99 percent. During the growing season, mineral soils are generally less than fully recharged, and actual *ET* was probably limited on at least the upland complex of the watersheds. In addition, some variation in *ET* calculations can be expected because short-term variations in soil moisture storage are not accounted for on the upland soils and because runoff values during a short period are influenced by antecedent conditions.

Monthly water balance estimates and potential *ET*'s (data not shown) varied greatly, probably because of the influence of antecedent conditions on runoff. High precipitation late in one month could result in high runoff in the following month, even though precipitation in the second month was low. Also, changes in soil water storage were not evaluated on a monthly basis.

TABLE 3

Mid-summer evapotranspiration estimates from water balance data and potential evapotranspiration, June 1 to September 1 (in inches)

Bog and year	P	R	S_b	ET	Potential ET
S-2					
1961	8.36	0.29	−1.79	9.86	14.05
1962	11.28	1.83	−1.39	10.84	12.48
1963	13.30	2.22	−0.57	11.65	12.88
1964	14.04	1.86	+1.12	11.06	12.89
1965	9.84	1.30	−1.27	9.81	11.71
1966	16.41	2.63	+0.97	12.81	13.68
S-6					
1965	9.64	1.21	−2.86	11.29	11.71
1966	15.74	2.31	−0.18	13.61	13.68

The data in tables 2 and 3 reflect *ET* from the total bog-upland complex because runoff was calculated on the basis of total watershed acreage. An attempt was also made to determine *ET* from only the bog areas. To minimize possible moisture contribution from the uplands, either in the form of saturated or unsaturated flow, estimates were made only for very dry periods. The criteria for selection of these periods were (1) low runoff, (2) low water tables, and (3) the same water table elevation at the beginning and end of the computation period (when presumably the water content of the peat was the same also). Only the actual area of peatland was used to calculate area-inches of runoff. The results for bog *S*-2 are given in table 4.

ET's computed from the water balance data are consistently less than potential values. *ET*'s for bog *S*-6 (data not shown) are also less than potential and are in general agreement with *S*-2 data.

TABLE 4

Mean daily evapotranspiration for selected drying periods computed from water balance data and potential evapotranspiration in bog S-2(1)

Dates	Mean temperature °F	Computed ET (inches)	Potential ET (inches)
1961			
6/17 to 7/3	66	.09	.17
7/4 to 8/4	65	.13	.15
8/6 to 8/11	66	.09	.15
8/17 to 8/26	62	.08	.13
8/29 to 9/6	62	.06	.12
1962			
6/16 to 6/26	62	.11	.13
8/29 to 9/5	56	.07	.10
1963			
8/15 to 9/7	60	.08	.11
10/16 to 11/20	46	.03	.04
1964			
7/19 to 8/20	62	.09	.14
1965			
6/30 to 7/13	56	.08	.12
7/12 to 7/20	62	.11	.14
7/25 to 8/2	59	.09	.13
8/3 to 8/17	64	.11	.14
8/18 to 9/3	54	.07	.09
1966			
6/19 to 6/30	68	.09	.17
7/1 to 7/13	70	.12	.18
7/22 to 8/3	64	.13	.15

(1) Evapotranspiration was computed for each period and then divided by the number of days to obtain mean daily values.

Part of the difference may be due to inherent problems in calculating potential *ET* for short periods by the Thornthwaite method (Pelton *et al.* 1960), although most drying periods lasted 2 weeks or longer. However, since these represent relatively dry periods with the bog water table often more than 12 inches (30 cm) below the average surface elevation, sufficient water may not be available to attain potential *ET*. A number of authors have reported on the importance of water levels to *ET* in peatlands (Novikov 1964, Virta 1966). Heikurainen *et al.* (1964) have also demonstrated a close correlation between water content of the peat soil and depth to ground water. In our study areas, the surface mosses or hummocks have been observed to dry out when the water table is low. Thus, during dry periods, water may not always be readily available to the growing vegetation, particularly black spruce which is very shallow-rooted on undrained peatlands (Heikurainen 1964).

In general, the data in this study indicate that potential *ET* as calculated by the Thornthwaite method could be used to approximate the water balance in ungaged peatlands on a long-term, seasonal basis. Only data on precipitation and water storage changes within the peatlands would be needed. During drying periods, however, and particularly when bog water tables reach lower depths in the peat, *ET* may be less than potential.

Both methods used here do present some problems in calculating *ET* on a short-term basis. Future studies are being planned which will make use of evapotranspirometers and energy balance methods to investigate the influence of various water table levels on total evaporative loss from these peatland watersheds.

REFERENCES

BAY, Roger R., Évaluation of an evapotranspirometer for peat bogs, *Water Resources Res.*, **2**, 437-442, 1966.

BAY, Roger R., Techniques of hydrologic research in forested peatlands, U.S.A., Paper to be presented at the 14th IUFRO Congress, Munich, 1967.

BOELTER, D.H., Water storage characteristics of several peats *in situ*, *Soil Sci. Soc. Am. Proc.*, **28**, 433-5, 1964.

EGGELSMANN, Rudolf, Die potentielle und aktuelle Evaporation eines Seeklima-Hochmoores, *Gen. Assembly Berkeley, Intern. Assoc. Sci. Hydrol. Publ.*, **62**, 88-97, 1963.

HEIKURAINEN, Leo, Improvement of forest growth on poorly drained peat soils. *Inter. Rev. of Forestry Res.*, **1**, 39-113, 1964.

HEIKURAINEN, L., PÄIVÄNEN, J., and SARASTO J., Ground water table and water content in peat soil. *Acta Forestalia Fennica*, **77**, 5-18, 1964.

LINSLEY, R.K., KOHLER, M.A., and PAULHUS J.C., *Applied hydrology*, 689 pp. McGraw-Hill Book Co., Inc., New York, 1949.

MOLCHANOV, A.A., *The Hydrological Role of Forests*, 407 pp. Acad. Sci. U.S.S.R. Inst. Forestry, Moscow, 1960.

NOVIKOV, S.M., Computation of the water-level regime of undrained upland swamps from meteorological data. *Soviet Hydrology: Selected Papers*, **1**, 1-22, 1964.

PELTON, W.L., KING, K.M., and TANNER, C.B. An evaluation of the Thornthwaite method for determining potential evapotranspiration, *Agron. J.*, **52**, 387-395, 1960.

ROMANOV, V.V., Some problems of the hydrophysics of swamplands, excerpts from *Hydrophysics of Swamplands*, pp. 232-273. Hydrometeorological Press, Moscow, 1961.

THORNTHWAITE, C.W. and MATHER, J.R. Instructions and tables for computing potential evapotranspiration and the water balance, *Publ. in Climatol., Drex. Inst. of Tech.*, vol. X, 185-311, 1957.

VIRTA, Juhani, Measurement of evapotranspiration and computation of water budget in treeless peatlands in the natural state, *Commentationes Physico-mathematicae*, **32**, 70 p., 1966.

VOROB'EV, P.K., Investigations of water yield of low lying swamps of western Siberia, *Soviet Hydrology: Selected Papers*, **3**, 226-252, 1963.

DISCUSSION

Intervention of Dr. M.J. HALL

Question: Does the speaker include any allowance for shrinkage or wastage of the organic soils in his calculations; or are water tables maintained sufficiently near the surface for such considerations to be neglected?

Answer: In our natural bogs the water table is quite near the surface and I believe shrinkage or subsidence is not a problem. However, this problem is recognized in drained organic soils and we plan to observe this during the treatments of our peat catchments.

Intervention of Henry W. ANDERSON

Question: In your bogs, how deep is the active water use layer? Have you done any Tritium dating of the deep water; is it old water?

Answer: The active water use layer appears to be within the upper one or two feet from the bog surface. This is similar to data reported by investigators in Finland and the U.S.S.R. It is often referred to as the "Active" zone.

We have not carried out any Tritium dating of water in our bogs.