1984

Predicting soil moisture depletion beneath trembling aspen

D. Mital

E. Sucoff

Recommended Citation

Mital, D. and Sucoff, E., "Predicting soil moisture depletion beneath trembling aspen" (1984). *Aspen Bibliography.* Paper 3980.
https://digitalcommons.usu.edu/aspen_bib/3980

Predicting soil moisture depletion beneath trembling aspen[1]

DAVID MITAL AND EDWARD SUCOFF
Department of Forest Resources, University of Minnesota, St. Paul, MN, U.S.A. 55108

Received April 15, 1982[2]
Accepted August 27, 1982

MITAL, D., and E. SUCOFF. 1983. Predicting soil moisture depletion beneath trembling aspen. Can. J. For. Res. **13**: 45–52.

Soil moisture and potential evapotranspiration were monitored in four stands of *Populus tremuloides* Michx. during two growing seasons. Measured soil moisture was compared with soil moisture predicted by four models: THIRSTY, SOGGY, Zahner's, and a simple water budget. THIRSTY, an original model incorporating many soil layers, root density, and a variable resistance to moisture flux, generally gave the best fit. Water uptake was related to relative root density.

MITAL, D., et E. SUCOFF. 1983. Predicting soil moisture depletion beneath trembling aspen. Can. J. For. Res. **13**: 45–52.

Durant deux saisons de croissance, on a observé l'humidité et l'évapotranspiration potentielle du sol de quatre peuplements de *Populus tremuloides* Michx. L'humidité mesurée du sol a été comparée à celle prédite à partir de quatre modèles: THIRSTY, SOGGY, Zahner et un simple budget hydrique. THIRSTY s'est généralement révélé comme le plus conforme à la réalité mesurée; il s'agit d'un modèle original qui intègre des données portant sur plusieurs horizons de sol, la densité du système racinaire et une variable mesurant la résistance à la fluctuation de l'humidité. L'absorption de l'eau a été reliée à la densité relative du système racinaire.

[Traduit par le journal]

Introduction

The ability to predict soil moisture is needed in hydrologic models and in quantifying the moisture factor in tree growth. The goal of this paper was to identify a relatively simple simulation model which could predict soil moisture beneath aspen (*Populus tremuloides* Michx.) stands throughout the growing season. Several workers (e.g., Johnston and Doty 1972) have used the water budget to explain soil moisture beneath aspen. Others have developed evapotranspiration functions as part of larger hydrologic models for predicting water yield from watersheds with aspen (Jaynes 1978; Leaf and Brink 1973, 1975; Troendle and Leaf 1980). These reports did not indicate how closely the models predicted soil moisture.

This paper compares how well four models predict soil moisture beneath aspen (*Populus tremuloides* Michx.) stands. One model, THIRSTY, is original and the others have been applied to different species: SOGGY (Grigal and Hubbard 1971), Zahner's (Zahner 1967), and the simple water budget. PROSPER (Goldstein and Mankin 1972), a model recently tried on aspen (Troendle and Leaf 1980), was not included partly because the behavior of aspen stomates remains controversial (Sucoff 1982), and the conductivity of the banded soils could not be assessed. The first part of this paper explains the origins of THIRSTY; the second compares the closeness with which the four models predict soil moisture.

Materials and methods for field data

Stand and soil descriptions

Field data were collected in 1979 and 1980 from four plots in Minnesota, two in St. Croix State Park (46° N, 93° W), and two on the United States Forest Service Pike Bay Experimental Forest (47° N, 94° W). Each overstory was uniform, well-stocked, and nearly pure aspen (Table 1). The Warba (Typic Eutroboralf) at Pike Bay (PB) is a loamy, well-aerated soil which supports good aspen growth. The Omega (Spodic Udipsamment) at the two St. Croix plots (SC1 and SC2) is a sandy soil with poorer growth potential.

The plots, while small (0.12–0.4 ha), were located in extensive continuous forest. On one plot, Pike Bay cleaned (PBC), all woody and herbaceous vegetation less than 12.7 cm dbh was removed on June 16, 1979, and again in July, 1980. Prior to cleaning, the PBC plot had the same understory as the adjoining uncleaned plot (PBU). Soil moistures were determined at least 20 m from the plot boundary.

Soil properties were determined by horizon (Table 2). Available water holding capacity (AWC) was defined as the water content at field capacity minus the water content at −1.5 MPa (−15 bars) matric potential. The latter value was determined in a ceramic plate pressure apparatus, while field capacity was the water content 48–72 h after a major storm fell on soils already near −0.03 MPa. With few exceptions this water content was considerably higher than that determined in the laboratory at −0.01 MPa for SC soils and −0.033 MPa for PB soils. Cassel and Sweeney (1974) have reported similar discrepancies. The soil properties of the two PB plots were similar, but drainage was slower on the uncleaned plot. Compared with SC1, SC2 (Table 2) had fewer bands of very fine sands alternating with medium sands. Certain bands in the SC soils retarded moisture flow for days. There was no evidence of a water table near the root zone in any plot.

Root distribution (Table 3) was determined by the trench

---

[1] Authorized as Minnesota Agricultural Experiment Station Scientific Journal Series No. 13019.

[2] Revised manuscript received August 16, 1982.

TABLE 1. Description of vegetation on Pike Bay (PB) and St. Croix (SC) plots

	PB	SC1	SC2
Basal area (m^2/ha)	34.3	22.0	19.3
Aspen basal area (% of total)	94(7)[b]	98	99(8)
No. of aspen/ha	630	1695	2547
Age in 1979 (years)	56	34	28
Site index at 50 years (m)	24	19	20
Predominate understory	*Acer spicatum* *Corylus cornuta* northern hardwoods	*Corylus* spp. dry-mesic shrubs	*Vaccinium* *angustifolium* Graminae
Shrubs[a] (stems/ha)	63 000	140 000	0

[a] *Vaccinium* and *Diervilla* were excluded.

[b] Number in parenthesis is percentage which is *Populus grandidentata*.

TABLE 2. Selected characteristics of Warba soils averaged for the Pike Bay plots and of the Omega soil on St. Croix 2

			% water by volume			
			In situ field capacity	Laboratory values (MPa)		AWC (cm/horizon)
Horizon	Depth (cm)	Texture[a]		−0.1	−1.5	
			Warba series			
A_2	0−30	vfsl	28.7	9.8	5.3	7.0
AB	30−38	vfsl	30.8	15.3	9.3	1.7
II B_2	38−67	cl	33.6	28.6	20.9	3.7
II B_3	67−95	scl	37.0	33.6	24.1	3.6
II C_1	95−168	scl	39.4	36.3	26.5	9.4
Total	0−168					25.4
			Omega series			
A	0−14	ls	15.4	6.7	5.6	1.4
B_{22}	14−56	s	10.2	5.0	3.8	2.7
B_{23}	56−69	s	7.6	2.2	2.2	0.7
C_1	69−91	s	7.0	—	2.1	1.1
C_2C_3	91−116	s	6.5	2.3	1.6	1.2
C_4C_5	116−141	s	7.2	2.0	1.7	1.4
$C_6C_7C_8$	141−180	s	9.4	2.9	1.8	3.0
C_9	180−185	s[b]	15.4	3.1	2.6	0.7
C_{10-13}[c]	185−259	s	9.8	—	1.7	5.8
Total	0−259					18.0

[a] vfsl, very fine sandy loam; cl, clay; scl, sandy clay; ls, loamy sand; s, sand.

[b] Contains narrow band of heavier texture.

[c] Alternating bands of fine and medium sand.

profile method (Bohm 1979). The counts were in one pit 1.5 m long; the standard deviations were based on five contiguous units, 30 × 30 cm. All living roots were counted without regard to plant species. At Pike Bay the root densities below 30 cm were the same on the cleaned and uncleaned plots (Table 3). At SC1, sinker roots went deeper than 2.3 m. At SC2, textural banding altered root distribution: at 2.3 m roots proliferated in a 1-cm-thick band containing clay; and at 1.8 m roots proliferated at the interface of a thin layer of gravel underlain by fine sand. Above or below these narrow bands of proliferation there were few roots.

Measurement of soil moisture and atmospheric variables

Soil moisture in 1979 was measured weekly or biweekly from June into September or October. In 1980, there were 10 biweekly measurements from May through September. The moisture content was determined gravimetrically for the surface 13 cm with a pooled sample of 10 cores, each 2 cm in diameter. Soil moisture below 13 cm was determined by neutron attenuation using field-calibrated probes. Three stands had seven access tubes; one had five. On SC plots, readings were taken 20, 30, 45, 61, 91, 122, 152, 183, 213, and 244 cm from mineral soil surface. On PB plots, the

TABLE 3. Density of roots in aspen stands sampled in October 1979. Numbers are roots per 1000 cm^2 of vertical surface (± are standard errors)

Soil depth (cm)	St. Croix		Pike Bay	
	Stand 1	Stand 2	Cleaned	Uncleaned
0–30	31.8±2.1	42.0±4.6	23.6±4.2	35.3±3.6
30–60	10.9±2.4	14.7±1.1	11.8±1.3	12.2±1.0
60–90	2.0±1.3	5.3±1.8	6.0±1.4	7.3±1.0
90–120	0.9±0.9	4.4±1.6	2.7±0.7	3.6±0.9
120–150	0.7±0.6	3.1±1.3	1.8±0.8	2.4±1.2
150–180	5.6±2.3	3.3±2.1	0.7±0.4	
180–210	1.3±0.9	2.9±0.7		
210	0.2	0.5		

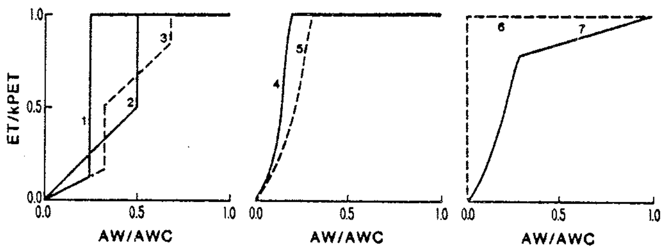

FIG. 1. Seven moisture resistance functions (MRF) used in the sensitivity analysis of THIRSTY. The y-axis is the ratio of actual evapotranspiration (ET) to potential evaporation (PE) × crop coefficient (k). The x-axis is the ratio of current available water (AW) to available water at field capacity.

deepest reading was at 183 cm.

Moisture content varied modestly among access tubes. For example, in 1979 the standard error of the mean moisture contents at any one date averaged 0.75 cm at SC (260 cm) and 2 cm at PB (200 cm). The standard errors of soil moisture change between readings were smaller, 0.1 cm at SC and 0.7 cm at PB.

Accumulated precipitation was measured concurrently with soil moisture and was prorated to a daily basis using records from the nearest weather station. This prorating introduced some error at Pike Bay. Solar radiation was measured 2 or 11 km from the plot in 1979 and 11 or 35 km in 1980. Temperatures and humidities were measured at stations 1 or 7 km from the plots. Wind data for St. Croix were averaged from stations 105 km north and 130 km south of the plot. Wind data for PB were collected 150 km north of the plot. The distance to the wind stations probably introduced error into the estimates of Penman potential evaporation (PE). PE was estimated for 1979 and 1980 using both Penman (1948, 1949) and Thornthwaite (1954) methods. In 1980, at Pike Bay, solar radiation data were missing for 20% of the days. On those days, Penman PE was determined by multiplying Thornthwaite PE by a monthly factor (1.07–1.35) determined as the ratio of Penman PE / Thornthwaite PE for days in that month when both measures were available.

Description of THIRSTY

Inputs, outputs, and parameters

THIRSTY was developed to use few dynamic inputs. Several inputs and all parameters of THIRSTY are listed below; the time frame is 1 day. PE: the daily potential evaporation was calculated by the equations of Penman (1948, 1949) or Thornthwaite (1954). Precipitation: interception was calculated from the values of Verry (1976) and Helvey and Patric (1965); and throughfall by subtraction of interception from precipitation. AWC_j: the available water at field capacity in each soil layer (j). AW_{mo}: the measured soil moisture at the beginning of the season. RRN_j: the relative root number in a soil layer calculated as (number of roots in layer j)/(total number of roots in the measured profile). The PB plots had 8 or 9 layers, the SC plots had 11 layers. When data in Table 3 were used the notation is observed RRN. Adjustments to RRN are described in the sensitivity analysis. N: the number of days it takes water above field capacity to drain from the profile. N values of 5 and 3 days were selected for PB and SC plots, respectively, based on inferences from Cassel and Sweeney (1974). k: the crop coefficient was determined as $k = (ET_m/PE)$ averaged for those periods between June 15 and September 1 when soil water was near AWC and there was presumably no deep seepage. Measured ET (ET_m) was set equal to the measured change in soil moisture plus 0.3 (interception) plus throughfall. The k was based on 20% of the observation days at PB and 30% of the days at SC. The final

Penman k values were 0.80 at PBU, 0.79 at PBC, 0.90 at SC1, and 0.86 at SC2.

MRF: the moisture resistance function quantifies the increased resistance to water movement through the soil and plants which occurs as the soil dries. Seven empirical relations were tried as representative of those in the literature (Fig. 1). A single MRF was used on SC plots because soil textures were similar among layers. PB soils were divided into a superficial layer (U) 30 cm thick and a lower layer (L) comprising the deeper soil. The outputs of THIRSTY include: ET_p and ET_{pj}; the predicted evapotranspiration from the entire profile or from an individual soil layer (ET_{pj}); AW_p and AW_{pj}, the predicted available soil water in the entire profile or in layer j (AW_{pj}); deep seepage, water lost through the bottom of the profile.

Computational steps

The complete documentation and program for THIRSTY is available on request. In brief, these computational steps are performed each day. (1) Daily PE is calculated. (2) Daily interception and throughfall are entered. If these are zero, proceed to step 3*c*. (3) Next ET_p is calculated in four sequential steps with $ET_p \leq k\text{PE}$. (*a*) First, 30% of interception is subtracted from kPE. If any kPE remains, proceed to 3*b*. (*b*) Next, throughfall is subtracted from kPE. If any kPE remains, proceed to step 3*c*. If any throughfall remains, it is added to the soil from the surface down. Each layer is brought to AWC before any water is added to the layer beneath it. When all layers are at AWC, the throughfall is added to an excess account. Water drains from the excess account in N days. (*c*) Daily ET_p is next met from the excess account until total ET = total kPE or the excess account is emptied. Once the excess account is empty, go to step 3*d*. (*d*) Finally, ET_p is met from AW with [1] $ET_p = \sum_j^n ET_{pj}$ where j to n refer to soil layers and

$$[2]\quad ET_{pj} = RRN_j{*}MRF_j{*}k\text{PE (remaining after step } 3c\text{)}$$

Equations 1 and 2 are written in accord with findings for annual crops (e.g., Taylor and Klepper 1973) that water absorption from a layer of soil is in direct proportion to the RRN of that layer. It is also written in accord with findings that depletion varies with soil moisture (e.g., Ritchie *et al.* 1972).

Prediction of soil moisture by THIRSTY

Criteria for evaluation

THIRSTY was evaluated by the closeness between predicted available water (AW_p) and measured available water (AW_m). Three criteria were used to judge closeness for single soil layers, groups of layers, or the entire profile: (*i*) $AW_p - AW_m$ on a specific date. In 1979 there were seven dates 7 to 14 days apart. In 1980 there were six dates 11 to 16 days apart. (*ii*) The average departure of $AW_p - AW_m$. This was determined by averaging the sum of the absolute values of $AW_p - AW_m$ for all the dates during a specified perod. (*iii*) The range of $AW_p - AW_m$ including the zero value at the start of the season. Range was always closely related to the average departure.

THIRSTY predicted actual soil moisture closely from mid-June into early September (Fig. 2, Table 4). Later in September, although leaves were still green, predictions became erratic, perhaps because of senescence (Gee and Federer 1972). The parameters used to obtain the fit for THIRSTY-observed RRN (Table 4) were derived mostly from functions unrelated to the model. N was induced from the literature, RRN was observed, and k was calculated with measurements and equations independent of the model's logic but including 20 (PB) or 30% (SC) of the same data set. Options for an MRF curve were from the literature but the best fit among these was determined by trial.

The sensitivity of THIRSTY to changes in parameters was systematically examined. N had little effect once values of 3 days or longer were used. Predictions varied with MRF, but among the MRF's resembling those accepted in the literature (e.g., Ritchie *et al.* 1972) changes were slight (Table 5).

The sensitivity of AW_p to changes in RRN was tested by altering RRN so as to minimize $AW_p - AW_m$ for each layer. In doing this, AW_p was reinitiated to AW_m after each measurement and the total RRN remained 1.0. In general, observed RRN's depleted the upper layers too quickly and the lower layers too slowly. Adjustments of RRN moderately improved predictions for individual layers but had little effect on prediction for the entire profile except for PBC 1980 (Table 4, THIRSTY-adjusted RRN versus THIRSTY-observed RRN). Several factors could help explain why uptake was not proportional to observed RRN at SC plots. Water may have migrated upward as the surface soil dried; also the upper 30 cm was proportionately richer in shrub, herb, and grass roots and these roots may be less effective in transpiration.

Among the parameters, changes in k had the largest effect on THIRSTY (Table 5) and in only three of the eight situations did the calculated k approach the best fit. The calculated k's were too low at PB and too high at SC2. The differences between measured and best-fit values of k may be a product of the model, but errors in estimating k and weaknesses in the concept of k are also involved. The calculation of k required assumptions on deep seepage, timing of rainfall, and constancy of plant resistance to water flux. The calculated PE may also have been in error. In applying THIRSTY to a new stand, a k of 0.84 would seem the safest first estimate (Table 6) but additional work on estimating k is needed.

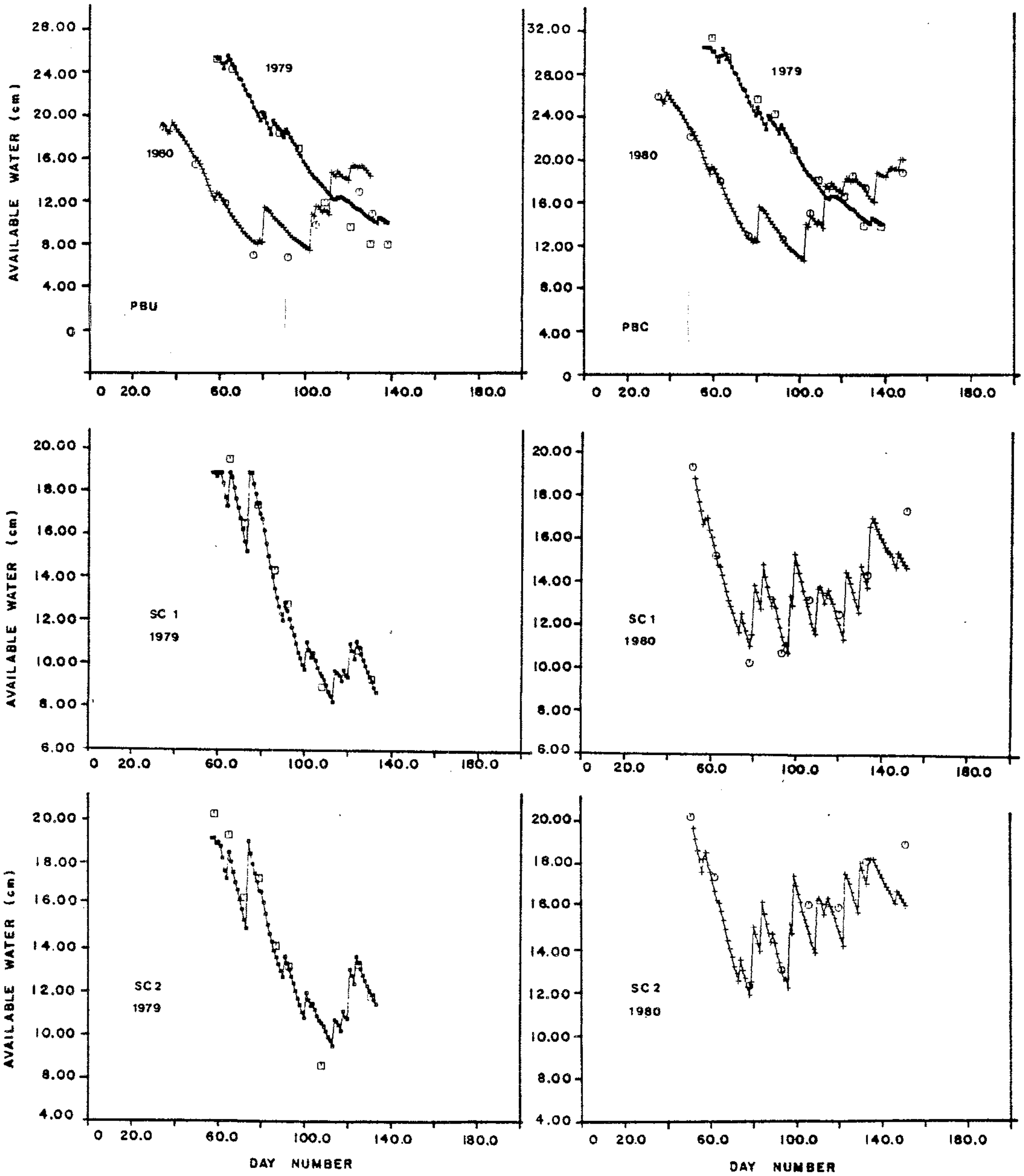

FIG. 2. The relation between measured available water (large open squares, 1979 and large open octagons, 1980) and available water predicted with THIRSTY. Plot PBU has $k = 0.78$, MRF = 4U 5L, $N = 5$. Plot PBC has $k = 0.79$, MRF = 4U 5L, $N = 5$. SC1 has $k = 0.90$, MRF = 4, $N = 3$. SC2 has $k = 0.86$, MRF = 4, $N = 3$. All plots have adjusted RRN. Days are counted from May 1. Profiles are predicted to 200 cm at PB and 260 cm at SC.

In summary, sensitivity analysis showed that the predictions of THIRSTY were very sensitive to k, moderately sensitive to the MRF, and insensitive to N values above 3. The observed RRN's gave as good predictions to total withdrawal as the adjusted RRN's except at PBC in 1980 (Table 4).

Comparison among models

THIRSTY was compared with three other simulation models as to how well they predicted total soil moisture in the profile throughout the season (Table 4). The previously described data set was used. The simplest model was a water budget in which $ET_p = k$PE until

TABLE 4. Comparison of how closely four models predicted available soil moisture in SC and PB stands, 1979 and 1980. Closeness of fit was evaluated by average departure (absolute value) between AW_p and AW_m and by the departure on last date of measurement. (For dates and parameters see Fig. 2)

Year	Plot	THIRSTY-adjusted RRN	THIRSTY-observed RRN	Zahner[a]	SOGGY	Simple water budget
		Average departure (cm of water)				
1979	SC1	0.4	0.7	1.0	0.4	0.6
	SC2	1.0	1.0	2.7	1.6	2.0
	PBU	0.8	0.9	1.2	2.2	1.0
	PBC	0.5	0.4	0.7	1.1	0.4
1980	SC1	0.7	0.6	4.8	2.9	4.2
	SC2	1.1	0.6	4.1	4.4	3.8
	PBU	1.5	2.0	1.9	2.9	1.8
	PBC	0.3	2.0	0.8	0.5	4.0
		Departure on September 1 (cm of water)				
1979	SC1	0.1	1.5	−1.8	−0.7	−0.6
	SC2	−0.9	1.2	−5.2	−2.8	−4.6
	PBU	2.5	2.9	3.6	4.5	−2.1
	PBC	0.7	−0.1	−0.3	1.4	−0.9
1980	SC1	−1.8	−0.4	−7.0	−4.1	−6.8
	SC2	−2.1	−0.6	−4.3	−5.1	−5.7
	PBU	2.6	3.3	3.2	4.6	−3.6
	PBC	−0.4	3.1	−0.2	0.7	−6.4

[a] MRF function was 1 at SC and 5 at PB.

TABLE 5. Examples of the effect of MRF on the average departure (cm of water) between AW_p and AW_m, 1979 and 1980 averaged. Other parameters are as in Fig. 2. U refers to the upper 30 cm of soil, L to the rest of the profile; the numbers 4, 5, and 7 refer to MRF's in Fig. 1

	Pike Bay plots			St. Croix plots	
	Average departure (cm)			Average departure (cm)	
MRF	PBU	PBC	MRF	SC1	SC2
4U 5L	0.8	0.4	4	0.5	1.0
4U 7L	1.1	0.4	5	0.5	1.0
			7	0.5	0.4

AW_p for the entire profile reached 0, an event that did not occur; deep seepage was not allowed. The Zahner (1967) and SOGGY (Grigal and Hubbard 1971; Wroblewski and Grigal 1975) models were run as described by their authors with these exceptions. In SOGGY the surface layer was set at 38 cm at PB and 68 cm at SC. Also, *k* as determined for THIRSTY was used in all models. The use of *k* derived from THIRSTY biased the comparison in favor of this model since an average of 25% of the data was used to determine *k*.

When the average departures were used to compare models, THIRSTY with adjusted RRN was consistently the best model (Table 4). THIRSTY with observed RRN was equally good except for the PB plots in 1980. Other models gave reasonable predictions only in some of the plot–year combinations. Because of the bias introduced by *k* from THIRSTY, the models were also compared using other values for *k*. Lower values of *k* at SC and higher values of *k* at PB generally improved the fit with all models. On SC plots, THIRSTY remained best at all *k*'s, but at PB, a *k* of 0.93 made SOGGY the superior model for 1979.

Conclusions

THIRSTY gave accurate predictions of AW by layer and for the entire profile beneath aspen stands from

TABLE 6. Effect of crop coefficients upon the average departure (absolute value) between predicted and measured soil moisture in centimetres of water. All other parameters for THIRSTY as in Fig. 2. Dates for PB are June 23 – August 29, 1979 and June 3 – September 2, 1980. Dates for SC are June 27 – September 2, 1979 and June 20 – August 28, 1980

Penman	PBU		PBC		SC1		SC2	
k	1980	1979	1980	1979	1980	1979	1980	1979
0.71	—	—	1.6	0.8	—	1.5	0.8	1.3
0.77	2.0	1.1	0.3	0.4	1.2	1.0	0.3	0.8
0.82	1.5	0.6	0.9	1.0	0.5	0.7	0.7	0.8
0.88	1.0	0.8	1.6	2.0	0.7	0.6	1.6	1.3
0.93	0.8	1.4	2.2	2.6	2.2	1.0	2.4	1.8
0.99	0.9	2.2	—	—	—	1.2	—	—
1.04	1.2	—	—	—	—	—	—	—
Fig. 2	1.5	0.8	0.3	0.5	0.7	0.4	1.1	1.0

mid-June through August (Table 4, Fig. 2). The generally good fit of THIRSTY is encouraging since except for the periods when *k* was determined the data set provided an almost independent test of this model. While alternative models, SOGGY, Zahner's and the simple water budget also gave reasonable predictions, they were somewhat less satisfactory particularly on SC plots (Table 4).

All four models suffered many of the known problems of modeling ET (e.g., Anonymous 1980). Not least among these, the crop coefficients were of uncertain accuracy. For example, the empirical crop coefficients differed unpredictably between the SC and PB plots. Refinement of crop coefficients for the entire growing season deserves the highest priority in future work.

Acknowledgements

This work was supported by the United States Department of Agriculture Forest Service grant No. 13–697 and Hatch Act funds.

ANONYMOUS. 1980. Comparison of Forest Water and Energy Exchange Models. 1978 IUFRO Workshop, Uppsala. *Edited by* S. Halldin. Elsevier Scientific Publishing Co., New York.

BOHM, W. 1979. Methods of studying root systems. Springer-Verlag, Berlin, Heidelberg, New York.

CASSEL, D. K., and M. D. SWEENEY. 1974. *In situ* water holding capacities of selected North Dakota soils. N.D. Agric. Exp. Stn. Bull. No. 495.

GEE, G. W., and C. A. FEDERER. 1972. Stomatal resistance during senescence of hardwood leaves. Water Resour. Res. **8**: 1456–1460.

GOLDSTEIN, R. A., and J. B. MANKIN. 1972. PROSPER: A model of atmosphere–soil–plant water flow. *In* Summer Computer Simulation Conf. Proc. pp. 1176–1181.

GRIGAL, D. F., and J. E. HUBBARD. 1971. SOGGY: An empirical evapotranspiration model for soils. Proceedings of the 1971 Summer Simulation Conference, July 19–21, 1971, Boston, MA. pp. 795–800.

HELVEY, J. D., and J. H. PATRIC. 1965. Canopy and litter interception of rainfall by hardwoods of eastern United States. Water Resour. Res. **1**(2): 193–206.

JAYNES, R. A. 1978. A hydrologic model of aspen-conifer succession in the western United States. U.S. Dep. Agric. For. Serv. Res. Pap. INT-213.

JOHNSTON, R. S., and R. D. DOTY. 1972. Description and hydrologic analysis of two small watersheds in Utah's Wasatch Mountains. U.S. Dep. Agric. For. Serv. Res. Pap. INT-67.

LEAF, C. F., and G. E. BRINK. 1973. Hydrologic simulation model of Colorado subalpine forest. U.S. Dep. Agric. For. Serv. Res. Pap. RM-107.

——— 1975. Land use simulation model of the subalpine coniferous forest zone. U.S. Dep. Agric. For. Serv. Res. Pap. RM-135.

PENMAN, H. L. 1948. Natural evaporation from open water, bare soil, and grass. Proc. R. Soc. London, Ser. B, **193**: 120–145.

——— 1949. The dependence of transpiration on weather and soil conditions. J. Soil Sci. **6**: 74–89.

RITCHIE, J. T., E. BURNETT, and R. C. HENDERSON. 1972. Dryland evaporative flux in a subhumid climate: III. Soil water influence. Agron. J. **64**: 168–173.

SUCOFF, E. 1982. Water relations of the aspens. Minnesota Agric. Exp. Stn. Tech. Bull. No. 338.

TAYLOR, H. M., and B. KLEPPER. 1973. Rooting density and water extraction patterns for corn (*Zea mays* L.). Agron. J. **65**: 965–968.

THORNTHWAITE, C. W. 1954. The determination of potential evapotranspiration. *In* The measurement of potential evapotranspiration. *Edited by* J. R. Mather. Publications in Climatology VII(1). John Hopkins University. pp. 218–225.

TROENDLE, C. A., and C. F. LEAF. 1980. Hydrology. *In* An approach to water resources evaluation of nonpoint silvicultural sources (A procedural handbook). Environmental Protection Agency Rep. No. EPA 600/8-80-102. pp. 111–173.

VERRY, E. S. 1976. Estimating water yield differences between hardwood and pine forests: an application of net precipitation data. U.S. Dep. Agric. For. Serv. Res. Pap. NC-128.

WROBLEWSKI, D. V., and D. F. GRIGAL. 1975. Observation and prediction of soil water under different types of vegetation. Minn. Acad. Sci. **41**: 12−14.

ZAHNER, R. 1967. Refinement in empirical functions for realistic soil moisture regimes under forest cover. *In* Forest hydrology. *Edited by* W. E. Sopper and H. W. Lull. Pennsylvania State University, State College, PA. pp. 261−274.