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Soil Model -- Heat, Water, and Salt Flow (2.3.6.)

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Abstract

A model has been developed for predicting soil temperatures from measured soil temperatures near the surface. This model appears capable of predicting soil temperatures within ± 2°C provided flow is one-dimensional. A model developed for predicting soil water content and potential as a function of time and depth has been developed. Plant root extractions and a wide variety of boundary conditions can be handled by the model. Limited tests show that it is fairly accurate for a wide variety of boundary conditions. A model to estimate salt and nutrient flow is in the early stages of development. Preliminary tests show it to yield results considerably in error.

Objectives

The objectives of this study are to develop practical models for heat, water, and salt flow that will allow for prediction of soil temperature, soil water content and potential, and soil water content in desert species. It is also necessary to make the models as practical as possible and to minimize the measurements necessary to use with the model.

Methods

The methods used have been to modify and extend existing models and to test them for validity against measured data. Sensitivity tests of the importance of soil properties and field measurements needed are also made to aid validation and process studies.

Findings

Soil Heat Flow Model

This model was the first investigated because it was the simplest and most useful for training purposes. A one-dimensional heat flow model has been devised for predicting soil temperature from a knowledge of soil properties and continuous measurements of soil temperature near the surface. Comparison of computed temperatures with measured temperatures indicate that soil temperature can be estimated within ± 2°C, provided reasonable constant soil thermal diffusivities are assumed and soil temperature profiles are made at some time once a week. A manuscript has been prepared and submitted to Soil Science Society of America Proceedings and has been accepted for publication. This manuscript is included as an appendix to this report. Further modifications are needed to extend this model to two and three dimensions.

Soil Water Flow Model

This model is much more complex than the heat flow model; consequently, much more effort has been, and will be, expended to attain a reasonable model. The model developed is only partially tested to date and is a modification of that of Hanks et al. (1969).

The principle modification involves the consideration of extraction by plant roots. The general flow equation for one-dimension is assumed to be

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(\frac{\partial H}{\partial z}\right) + A(z). \qquad [1]$$

Where θ is volumetric water content, t is time, z is depth, K is hydraulic conductivity, H is hydraulic potential (or head), and A(z) is the plant root extraction function. The numerical approximation form of the plant root extraction function is written as follows

$$A(z) = \frac{(H\ ROOT + R\ RES \cdot z - h_z - S_z) \cdot RDF(z) \cdot K_z}{Az} \qquad [2]$$

where h_z is the water potential at depth z

S_z is the salt (osmotic) potential at depth z

h_z is the soil pressure potential at depth z

K_z is the hydraulic conductivity at depth z

RDF(z) is the proportion of the total active roots in depth increment Az

R RES is a root resistance term to reflect the resistance to water flow inside the root

H ROOT is an "effective" water potential in the root

K_z and h_z are assumed to be unique functions of soil water content which can be determined from measurements of soil water properties.

RRES is, at the moment, an unknown quantity but is assumed to have a value of 1.0 to almost 2.0. If it is 1.0, then there is no resistance to flow in the root. We are assuming it is constant with depth and is 1.05.

H ROOT is dependent on plant, soil and climatic conditions. Physically we envision it as the plant water potential at zero depth. In the model, a value of H ROOT will be "hunted" for until the plant root extraction over the total profile is equal to potential transpiration provided the value of H ROOT is higher than HWILT. HWILT is the value of plant water potential below which the plant will not go, and thus "wilting" will occur. The value of H ROOT will depend on climatic conditions since climate conditions define potential transpiration. The value of H ROOT will depend on soil conditions since h_z, K_z and S_z will be soil properties (which will vary greatly from wet to dry soil). H ROOT will depend on plant conditions since they govern RDF(z). In the model H ROOT is bounded on the wet end (H ROOT = 0.0) and the dry end by (H ROOT = HWILT).

Input data needed for the solution and any problem are:

1. Soil properties-h-θ and K-θ curves covering the range of water contents to be encountered in the problem. The value of θ saturated and θ air dry must also be known.
2. θ vs. z and S vs. z at the beginning, t = 0, of the problem.
3. Plant properties, RDF(z) and value of HWILT.
4. Boundary and climatic properties - these include the potential evapotranspiration and potential transpiration (from which potential evaporation can be deduced) as a function of time. Basically this data will come from climatic variables of solar or net radiation, air temperature, air humidity, wind speed, and the proportion of ground covered by actively transpiring plants. Potential infiltration, a function of precipitation, is also needed.
5. Presence or absence of water table or layer resistricting water flow at the lower boundary.

Output data are:

1. Cumulative evapotranspiration, transpiration, and evaporation as a function of time.
2. Soil water content, θ, potential, h, as a function of time and depth.
3. The value of HROOT as a function of time.

Soil properties used for the computation reported herein are listed in Table 1. Condition A and B are reported and used in the analysis to test the effect of different properties on the results.

We have checked the model predictions against measurements made at Vernal, Utah during 1970. These data are for an agricultural crop (oats) and included artificial precipitation (sprinkler irrigation). They are used because no measurements are currently available for desert conditions.

Table 2 shows a comparison of predicted and potential evapotranspiration and infiltration for the 10 day period, assuming a 45 mm root zone and soil properties condition A. There were 3.27 cm of irrigation applied between 36 and 41.2 hours with no runoff. The model predicted 2.95 cm infiltration and 0.32 cm of runoff and that ET was slightly less than potential before irrigation and from 144 to 240 hours after irrigation. It also predicted that transpiration was less than potential from 144 to 240 hours. Evaporation was predicted to be less than transpiration from 0.36 and 192 to 240 hours.

Table 1. Soil properties used for computations made. Vernal sandy clay loam. A and B are different conditions assumed.

Water Content	Hydraulic Conductivity	Pressure Potential	
		A	B
0.02	3.4×10^{-9} cm/hr.	$-8.5 \times 10^{+5}$ cm	$-8.5 \times 10^{+5}$ cm
.04	1.7×10^{-8}	$-2.2 \times 10^{+5}$	$-3.6 \times 10^{+5}$
.06	5.4×10^{-8}	$-5.8 \times 10^{+4}$	$-1.5 \times 10^{+5}$
.08	1.7×10^{-7}	$-1.5 \times 10^{+4}$	$-6.4 \times 10^{+4}$
.10	4.8×10^{-7}	$-8.0 \times 10^{+3}$	$-2.7 \times 10^{+4}$
.12	1.5×10^{-6}	$-4.9 \times 10^{+3}$	$-1.5 \times 10^{+4}$
.14	4.5×10^{-6}	$-3.0 \times 10^{+3}$	$-7.8 \times 10^{+3}$
.16	1.4×10^{-5}	$-1.85 \times 10^{+3}$	$-3.8 \times 10^{+3}$
.18	4.5×10^{-5}	$-1.12 \times 10^{+3}$	$-1.5 \times 10^{+3}$
.20	1.1×10^{-4}	$-6.7 \times 10^{+2}$	$-7.7 \times 10^{+2}$
.22	2.7×10^{-4}	$-4.1 \times 10^{+2}$	$-4.1 \times 10^{+2}$
.24	6.1×10^{-4}	$-2.5 \times 10^{+2}$	$-2.5 \times 10^{+2}$
.26	1.5×10^{-3}	$-1.65 \times 10^{+2}$	$-1.65 \times 10^{+2}$
.28	3.5×10^{-3}	$-1.15 \times 10^{+2}$	-1.15×10^{2}
.30	9.0×10^{-3}	$-8.5 \times 10^{+1}$	-8.5×10^{1}
.32	2.1×10^{-2}	$-6.6 \times 10^{+1}$	-6.6×10^{1}
.34	3.5×10^{-2}	$-4.8 \times 10^{+1}$	-4.8×10^{1}
.36	6.0×10^{-2}	$-4.13 \times 10^{+1}$	-4.13×10^{1}
.38	1.0×10^{-1}	$-3.44 \times 10^{+1}$	-3.44×10^{1}
.40	1.7×10^{-1}	$-2.73 \times 10^{+1}$	-2.73×10^{1}
.42	3.1×10^{-1}	$-2.10 \times 10^{+1}$	-2.10×10^{1}
.44	5.4×10^{-1}	$-1.34 \times 10^{+1}$	-1.34×10^{1}
.46	8.8×10^{-1}	-6.98	-6.98
.48	1.3	0	0

Table 2. Comparison of predicted and potential evapotranspiration (ET), transpiration (T), evaporation (E), and infiltration (I), for oats at Vernal, Utah, 1970. Beginning of period was July 28. Root extraction in top 45 cm of soil, condition A.

	0-36	36-41.2	41.2-48	48-72	72-96	96-120	120-144	144-168	168-192	192-240
Potential ET cm	1.11cm	-	0.21cm	0.51cm	0.71cm	0.77cm	0.65cm	0.75cm	0.69cm	1.78cm
Predicted ET cm	1.03	-	.21	.50	.70	.78	.65	.72	.52	.83
Potential T cm	0.99	-	.19	.46	.63	.69	.58	.68	.62	1.60
Predicted T cm	1.00	-	.19	.45	.63	.70	.57	.66	.45	.71
Potential E cm	0.10	-	.02	.05	.07	.08	.06	.08	.07	.18
Predicted E cm	0.03	-	.02	.05	.07	.08	.08	.07	.06	.12
Potential I cm	--	3.27	-	-	-	-	-	-	-	-
Predicted I cm	--	2.95	-	-	-	-	-	-	-	-

Table 3 shows a comparison of measured and predicted infiltration, evapotranspiration, and water flow upward from a water table for the 10-day period. Three different root distribution-soil property relations are shown. All of the predictions underestimate infiltration slightly. Evapotranspiration predicted by the 45 cm root extraction, soil condition A, assumption was essentially the same as measured evapotranspiration. Where 30 cm root extraction was assumed, ET was predicted to be about 2 cm low. Water flow upward from the water table was similar for all soil-root conditions assumed and was 0.2 to 0.5 cm to high. Water flow upward from the water table WFU was measured as the WFU - ET-I-ΔS where ΔS is change in soil water storage. ET was measured with lysimeters where no water flow upward from the water table was allowed. In general, soil condition A with 45 cm root extraction gives overall results closer to the measured data than either of the other two conditions. The models all assumed uniform basic soil properties throughout, which is probably not too realistic. The agreement between measured and predicted values using either of the assumed soil properties with 45 cm root extraction is probably sufficiently good for most purposes. Further refinements in the model may be necessary to include layered soil situations if they are much different. The analysis does show the importance of knowing the plant root extraction patterns and the soil properties with high accuracy.

Figure 1 shows the soil water content profiles at the end of the 10 day period for the three soil-root situations assumed. All of the three situations fit the measured data reasonably well but the 30 cm root extraction predictions appear better near the surface. However, the 30 cm root extraction assumption predicted total ET 2 cm low.

Table 3. Comparison of predicted and measured infiltration, evapotranspiration, evaporation and transpiration as influenced by root extraction depth and soil properties for 10 day period starting on July 28, 1970 at Vernal, Utah.

	Measured	Condition A 45cm RE	Condition A 30cm RE	Condition B45cm RE
Infiltration	3.28 cm	2.95 cm	3.04	3.01
Evapotranspiration	6.04	6.01	4.12	5.79
Transpiration	?	5.37	3.45	5.02
Evaporation	?	.64	.67	.77
Water Flow upward from water table	2.06	2.44	2.27	2.58

Figure 2 shows the predicted values of HROOT as a function of time for the 10 day period. Before the irrigation, and from 5 to 10 days, the 30 cm root extraction-condition A computation predicted HROOT=lowest value allowed which was -15 bars. Neither of the computations assuming 45 cm root extraction predicted HROOT = -15 bars before irrigation. Soil condition B caused the predicted value of HROOT to decrease to -15 bars about one day sooner than soil condition A. Whenever the predicted value of HROOT was greater than -15 bars, transpiration was equal to potential transpiration. The 30 cm root extraction computations ended up giving lower predictions of ET over the 10 day period because HROOT reached -15 bars sooner.

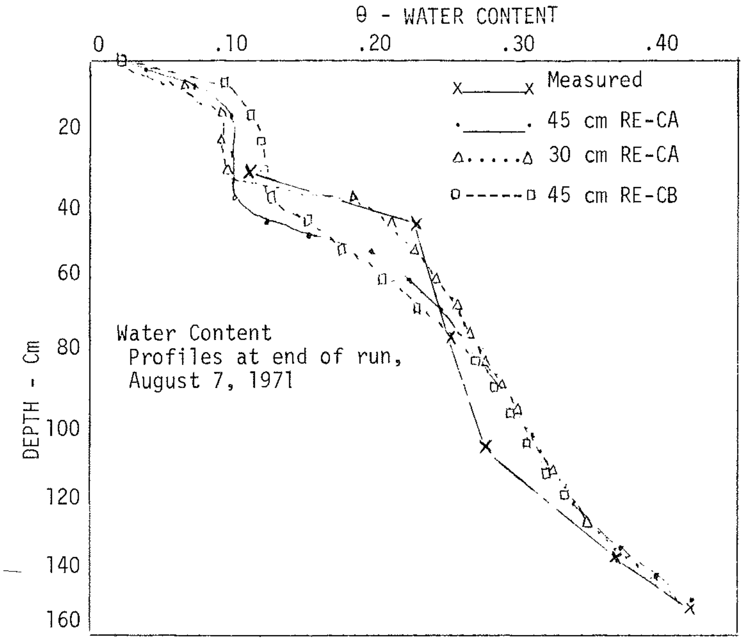


Figure 1. Soil water content profiles at the end of 10 day period for the three soil-root situations assumed.

Salt Flow Model

This model has not, at present, been developed beyond a very simple stage. The problem is very complicated because both water flow and interaction with the soil material have a large influence on salt movement.

Consequently, the present model includes only the movement of salts carried along with the water. No interaction or exchange with the soil has been considered. The interaction or exchange functions will be very complicated because each anion or cation may react differently.

Figure 3 shows a comparison of predicted and measured soil water content profiles during infiltration. Figure 4 shows predicted and measured electrical conductivity for the same flow system. Salt was added when the soil was first wet for one hour, after which nearly salt free water was added.

The data show quite good agreement between predicted and measured water content profiles. However, the agreement of salt profiles is very poor. The salt concentration peaks do not agree nor does the volume of salt in the soil agree. It is apparent that the neglect of exchange and interaction with the solid soil material has a large influence on salt flow.

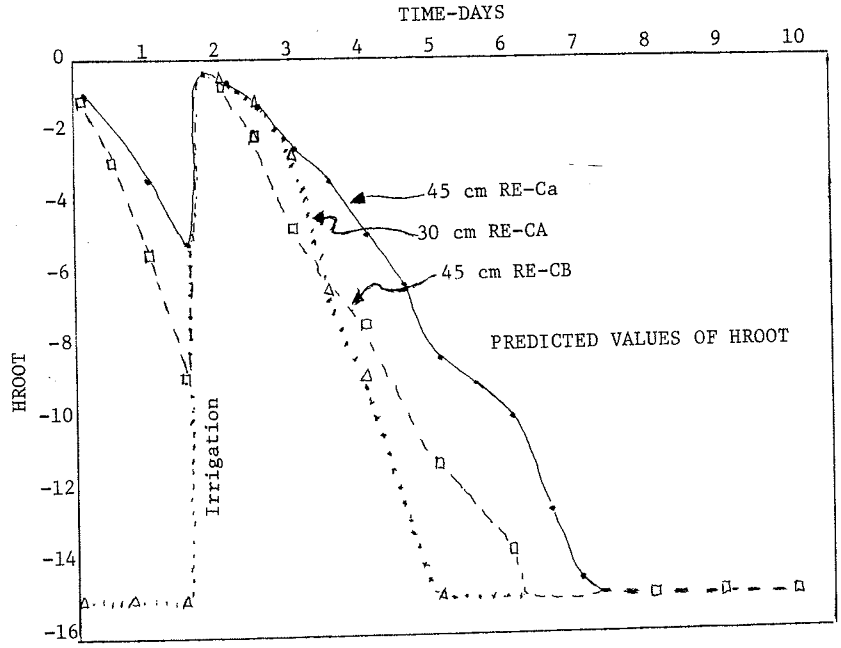


Figure 2. Predicted values of HROOT as a function of time for the 10 day period.

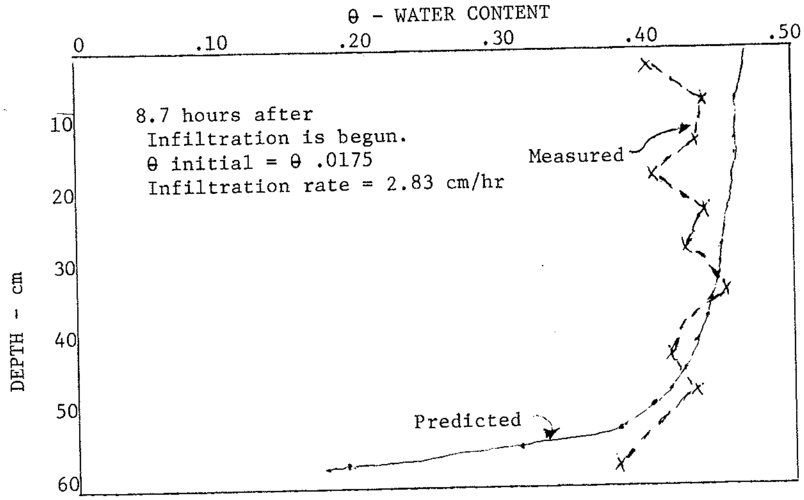
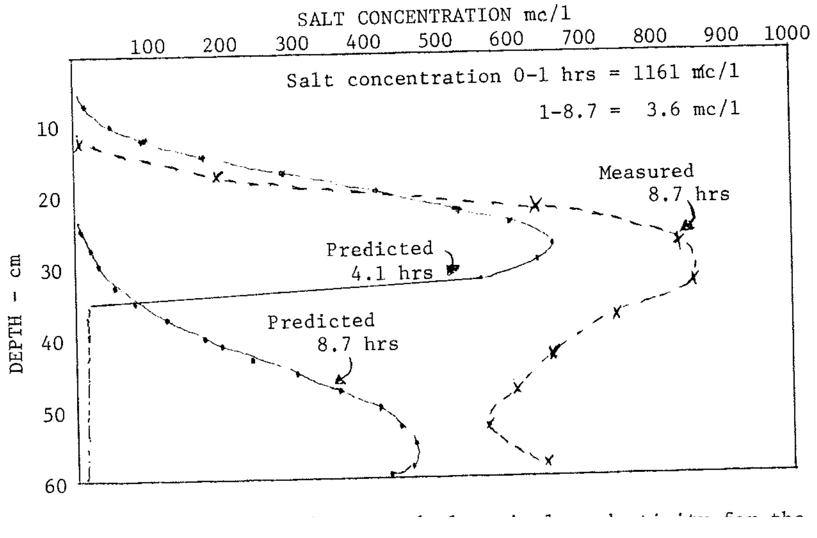


Figure 3. A comparison of predicted and measured soil water content profiles during infiltration



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Hanks, R. J., A. Klute, and E. Bresler. 1969. A numeric method for estimating infiltration, redistribution, drainage and evaporation of water from soil. Water Res. Res. 1:1064-1069.

APPENDIX

Soil Temperature Estimation by a Numerical Method[1]

R. J. Hanks, D. D. Austin, and W. T. Ondrechen[2]

Abstract

A numerical method for computing soil temperature as a function of time and depth was devised. The method allows for variable soil properties as a function of depth and required measured soil temperature at or near the soil surface. Computed and measured soil temperatures agreed within 1.0C when actual soil thermal properties were used for the computation. Computed and measured soil temperatures agreed within 1.5C when soil thermal diffusivity was assumed constant at 0.20 cm^2 min^{-1}. Actual values varied with depth from 0.21 to 0.29. Where the thermal diffusivity was assumed uniform at 0.45 cm^2 min^{-1}, temperature errors grew from 1.0 to 1.7C after three days to 1.7 to 3.1C after six days.

Introduction

The temperature of the soil is a basic property needed to evaluate many biological and physical processes in the soil-plant-animal ecosystem. Since the soil temperature varies both with time and depths on an annual and a daily scale it is usually not sufficient information to measure soil temperature at one time or one depth. This paper represents an attempt to develop and test a procedure for estimating soil temperature as a function of time and depth from a minimum of measurements.

The recent paper by Wierenga and de Wit (5) which was published after this work was essentially completed, is similar in many ways to this paper. They report good agreement between computed and measured temperature in wet soils but significant differences in dry soil for part of the day. They attribute part of this difference to changes in apparent thermal conductivity with temperature. They reported measurable errors due to changes of thermal diffusivity caused by changes in soil temperature during the day.

The partial differential equation describing soil temperature, T, as a function of depth, z, and time, t, in one dimension is

$$\frac{\partial T}{} = \frac{\partial}{\partial z} \left[\alpha \frac{\partial T}{\partial z}\right] \qquad [1]$$

where α is the thermal diffusivity (which in general may be a function of time and depth). The thermal diffusivity is equal to the ratio of thermal conductivity to heat capacity. As described by de Vries (1) the thermal conductivity is dependent on basic soil constituents, soil water content, bulk density, and temperature. The heat capacity, Cv, of most soils can be approximated by the following equation where soil organic matter is assumed zero and the specific heat (mass) of the solid soil material is taken as 0.2 cal g^{-1} $°C^{-1}$

$$C_v = \rho_b \times 0.2 + \theta \times C_w \qquad [2]$$

where ρ_b is the bulk density and θ is the fractional water content (volume).

Numerical Procedure

To predict soil temperature using equation [1], it is necessary to know the initial and boundary conditions of the particular problem. Analytical solutions to equation [1], assuming a constant thermal

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diffusivity and a sinusoidal temperature fluctuation at the soil surface as given by deVries (1), is often applied to soils. This solution yields somewhat inaccurate values because of non-uniform thermal diffusivity and non-sinusoidal soil surface temperature. To eliminate these problems we suggest solving equation [1] with a numerical approximation as follows:

$$\underline{Ti, j - Ti, j\text{-}1} = \frac{(Ti\text{-}1,j - Ti,j)_{\alpha_{i-1/2,j}} - (Ti,j - Ti = 1,j)_{\alpha_{i + 1/2,j}}}{\Delta z^2} \qquad [3]$$

where "i" is the subscript denoting the "jth" time increment at a time j·Δt. An equation can be written for each depth increment for a given time. If the temperature for all depth increments at time "j-1", Δt and boundary conditions are known, a series of equation with the same number of unknowns can be formed and solved to yield the temperature for all depth increments at time "j·Δt". The procedure is a modification of that used by Hanks and Bowers (2) and Hanks _et al_., (3) for soil water flow. A high speed digital computer is convenient to make the computations.

The procedure involved the following steps:

a. Input data are fed into the computer. These data included the initial temperature as a function of depth at the beginning of the computation, the surface temperature as a function of time, the thermal conductivity and heat capacity as a function of depth, Δz, and the termination time. For computations described herein the bottom boundary condition was at the depth below which no heat flow occurred (96 cm in the computations herein).

b. The solution of the temperature as a function of depth at the end of the time increment, Δt, is done as described by Hanks and Bowers (2). The data are then printed out.

c. The new temperature as a function of depth just computed is used as initial conditions and, provided the time is less than the termination time, the new boundary conditions are chosen. The process is then repeated from step b above until termination is reached.

The details of this method are different from those of Wierenga and de Wit (5) but the general approach is similar.

Procedure for Testing the Method

The soil temperatures computed for various thermal conductivity and heat capacity functions with depth were computed for a day. The initial and boundary conditions used were taken from actual data measured on July 1969 was reported by Hanks _et al_. (4). Measurements were made at Logan, Utah in an oat field with a fairly thin stand. The computed data as a function of depth and time were available for comparison with the measured data. The thermal diffusivity was estimated by the method of de Vries (1) from soil properties which included soil water content, general thermal properties of the solid soil material and bulk density assuming a constant temperature of 25C. The heat capacity was computed from equation [2].

Results

The comparison of the computed temperature at 6 and 16 cm compared with the measured temperature is shown in Figure 1. The measured soil temperature at 1 cm, which was used for the upper boundary condition for the computed solution, is also shown. The soil properties and the initial temperature used for the computation are listed in Table 1. The data show that the computed and measured temperatures at 6 and 16 cm agree within ±1C. Thus, it is concluded on the basis of these data that the computer solution of soil temperature using measured data at 1 cm and measured initial soil temperature and estimated soil thermal properties gives predicted temperatures at all depths sufficiently accurate for most purposes.

Since the data needed to estimate soil thermal properties are not always available, it was decided to determine what variations in the soil thermal diffusivity would do to computed soil temperatures.

Table 2 shows a summary of the soil temperature at different times for several depths using different soil properties compared with measured data. The data show that all of the different properties assumed yielded predicted temperatures at the end of one day that were within 1.2C of the measured temperature where the average thermal diffusivity was between about 0.20 and 0.55 cm^2/min. The least difference bewteen measured and computed temperature was found for the computations where α varied with depth as would be expected.

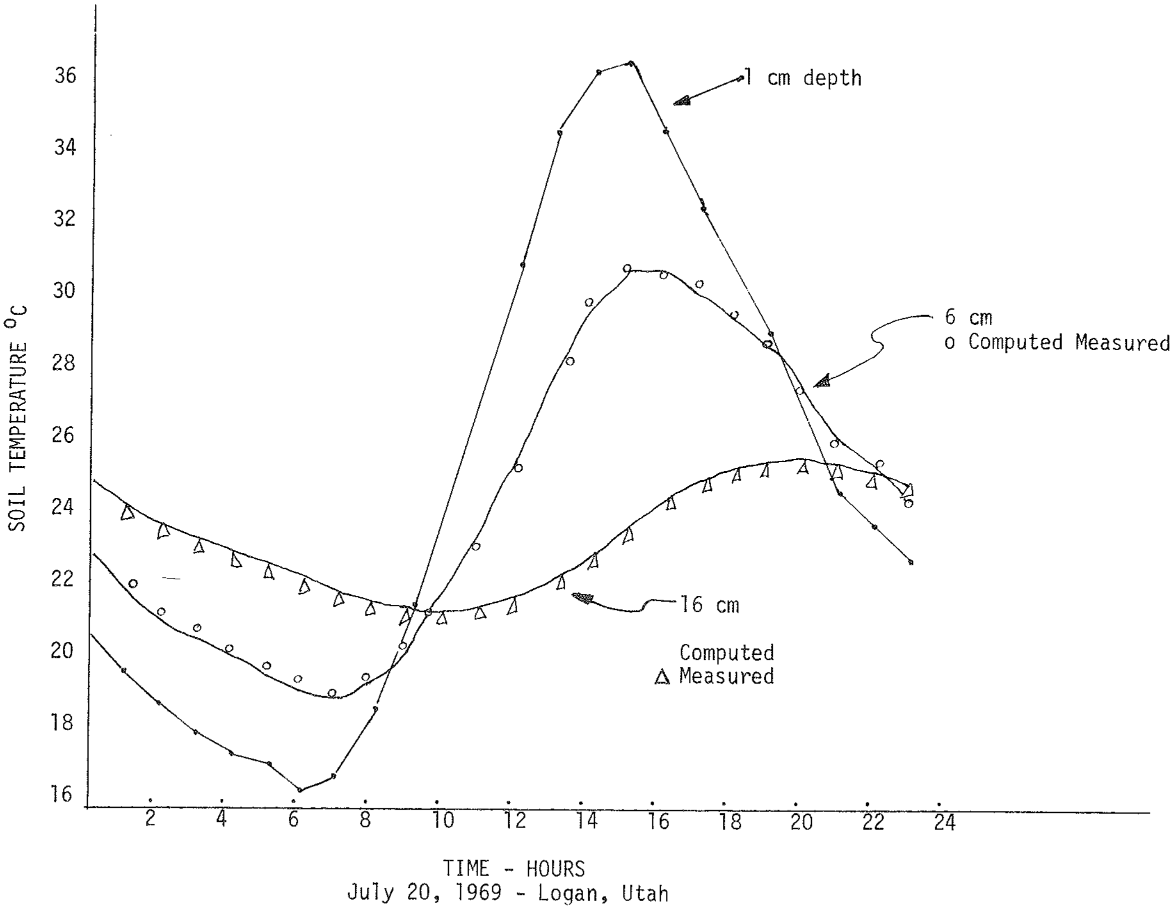

Figure 1. Comparison of computed and measured soil temperature as a function of depth and time using the soil thermal properties shown in Table 1.

Table 1. Soil properties and initial temperature for a Millville silt loam on July 20, 1969 used for comparison of computed and measured temperature. The bulk density of the soil is approximately 1.2 g cm^{-3}.

Depth cm	Temp at 0000 hours C	α $cm^2\ min^{-1}$	Θ	$\bar{k}$ cal $cm^{-1} min^{-1} {}^\circ C^{-1}$	C_v cal $cm^{-3} {}^\circ C^{-1}$
1	20.8	0.28	.01	.07	.25
6	24.0	0.27	.02	.07	.26
11	24.6	0.29	.04	.08	.28
16	24.2	0.28	.05	.08	.29
21	23.8	0.25	.08	.08	.32
26	23.4	0.26	.11	.09	.35
31	22.8	0.24	.14	.09	.38
36	22.2	0.22	.16	.09	.40
41	21.7	0.22	.17	.09	.41
46	21.2	0.21	.18	.09	.42
51	20.8	0.21	.18	.09	.42
56	20.4	0.21	.19	.09	.43
61	20.1	0.23	.19	.10	.43
66	20.0	0.23	.19	.10	.43
71	19.8	0.23	.19	.10	.43
76	19.6	0.23	.20	.10	.44
81	19.5	0.23	.20	.10	.44
86	19.4	0.23	.20	.10	.44
91	19.3	0.23	.20	.10	.44
96	19.2	0.23	.20	.10	.44

Table 2. Comparison of measured and computed soil temperature for July 20, 1969 at Logan, Utah assuming different soil thermal properties. The measured soil temperature at 1 cm depth was used for the boundary conditions and the initial conditions are listed in Table 1.

α assumed	Depth					
cm^{2}min^{-1}	6 cm		16 cm		31 cm	
	16 hrs	23 hrs	12 hrs	23 hrs	12 hrs	23 hrs
	measured temperature					
	31.2C	24.4C	21.9C	25.2C	22.0C	23.2C
	computed temperature					
Variable*	31.2	24.8	21.9	25.2	22.0	22.8
0.99	33.2	24.0	23.0	25.1	20.8	24.8
.91	33.1	24.1	22.8	25.2	20.8	24.7
.55	32.2	24.4	22.6	25.3	21.4	24.0
.50	32.4	24.4	22.0	25.4	21.3	24.0
.45	32.2	24.5	22.0	25.5	21.4	23.9
.37	31.9	24.7	21.9	25.5	21.7	23.6
.25	31.2	25.0	21.9	25.5	22.2	23.1
.23	31.0	25.1	22.0	25.4	22.3	23.0
.20	30.8	25.2	22.0	25.4	22.5	22.9
.06	27.3	26.0	23.5	24.2	23.1	23.0

*varies with depth as given in Table 2.

It would appear from these data that reasonably accurate estimates of soil temperature could be made by assuming reasonable values of thermal diffusivity that were constant with time and depth.

To determine the effect of longer time periods on errors, computations were made for several days where measured data were available. These results are shown in Table 3. Where the thermal diffusivity varied with depth, but was assumed constant with time, the difference between measured and computed temperature was 0.1 to 0.8C on July 11 and July 14. Thus after 6 days and 9 hours there appeared to be no appreciable "growth" of error. The computed soil temperature, where a uniform value of thermal diffusivity of 0.20 was assumed, varied from 0.1 to 1.4C on July 11 and from 0.1 to 0.9C on July 14. Again "growth" of error appeared to be small.

The largest difference between measured and computed soil temperature was found where the thermal diffusivity was assumed to be 0.45. The temperature difference between measured and computed temperatures varied from 1.0 to 1.7C on July 11 and from 1.7 to 3.1C on July 14. There was evidence of a definite "growth" of errors. The errors did not "grow" as seriously at 6 cm as at 61 cm. This is undoubtedly due to the larger influence of the measured boundary conditions on the computed temperature near the surface compared to computations made at large distances from the measured temperatures. However, even if the diffusivity were overestimated by about a factor of two (α = .45 for the data of Table 3) computed temperature would agree with measured temperatures within 2C for three days. Thus, based on the results of these computations, it would appear that estimates of soil temperature at any depth at any time would be no more in error than 2C provided measurements were made of temperature profiles once every three days, and the thermal diffusivity were off by no more than a factor of two. This conclusion applies for a condition where the soil was slowly drying out due to evapotranspiration but may not apply for rainy periods or where irrigation water was applied.

Table 3. Comparison of computed and measured soil temperatures for several days at Logan, Utah during July 1969. Initial conditions taken from measured soil temperatures on July 8 at 07 hours. Boundary conditions taken from soil temperature measurements at 1 cm.

Day	Hour		Depth				
			1	6	16	31	61
8	07	Measured	13.5 C	14.5 C	17.9 C	19.6 C	18.5 C
11	16	Measured	37.8	32.2	25.1	21.1	19.2
"	"	α=variable*	"	32.4	24.3	21.0	19.7
"	"	α=0.20	"	31.8	23.7	21.2	19.4
"	"	α=0.45	"	33.8	26.8	22.1	20.8
14	16	Measured	36.9	32.4	26.5	22.7	20.0
"	"	α=variable	"	32.9	26.1	22.8	20.8
"	"	α=0.20	"	32.5	25.6	23.0	20.8
"	"	α-0.45	"	34.1	28.5	24.5	23.1

*data from Table 1

As reported by Wierenga and de Wit (5) the temperature differences between computed and measured values would be expected to be greater if the soil had been bare and dry due to greater temperature variation at the soil surface.

It would undoubtedly be very important to measure soil temperature below the soil surface at a sufficient depth that no evapotration of water occurs below the measured depth. This analysis applies to one-dimensional steady state only. Further extensions for the analysis are needed for two- or three-dimensional problems.

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