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Department of Energy
Washington, DC 20585

SEP 16 1992

Mr. Joseph J. Holonich, Director
Repository Licensing & Quality Assurance
Project Directorate
Division of High-Level Waste Management
Office of Nuclear Material Safety
and Safeguards
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Reference: Ltr, Roberts to Holonich, dtd 6/29/92

Dear Mr. Holonich:

In Phase I reviews of the U.S. Department of Energy's (DOE) Study Plans 8.3.1.2.2.1, "Characterization of the Unsaturated-Zone Infiltration," and 8.3.1.9.2.2, "Water Resource Assessment of Yucca Mountain, Nevada," the U.S. Nuclear Regulatory Commission (NRC) requested that DOE provide references cited in the study plans that are Not-Readily-Available (NRA) in the public domain (enclosures 1 and 2).

Enclosure 3 contains the references requested for Study Plan 8.3.1.2.2.1, and Enclosure 4 contains those for Study Plan 8.3.1.9.2.2. ~~One reference (Gibbons, D.C., 1986, "The Economic Value of Water, Resources of the Future," Washington, D.C.) for Study Plan 8.3.1.9.2.2 is a copyrighted document, and DOE is not at liberty to copy and distribute multiple copies of it. Only the cover and reference pages are provided.~~ A concern expressed in NRC's Phase I review letter for Study Plan 8.3.1.9.2.2 with respect to groundwater in human intrusion scenarios was responded to in an earlier letter (reference).

If you have any questions, please contact Mr. Chris Einberg of my office at 202-586-8869.

Sincerely,

John P. Roberts

John P. Roberts
Acting Associate Director for
Systems and Compliance
Office of Civilian Radioactive
Waste Management

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Enclosures:
1. Ltr, 5/31/92, Linehan to
   Shelor, w/encl
2. Ltr, 5/4/92, Holonich to
   Roberts, w/encl
3. NRA References in Study
   Plan 8.3.1.2.2.1 (Not Record Material)
4. NRA References in Study
   Plan 8.3.1.9.2.2 (Not Record Material)

cc: w\enclosures on the Shelf
Alice Cortinas, CNWRA, San Antonio, TX

cc: w\enclosures
C. Gertz, YMPO
R. Loux, State of Nevada
T. Hickey, Nevada Legislative Commission
M. Baughman, Lincoln County, NV
J. Bingham, Clark County, NV
B. Raper, Nye County, NV
P. Niedzielski-Eichner, Nye County, NV
G. Derby, Lander County, NV
P. Goicoechea, Eureka, NV
C. Schank, Churchill County, NV
F. Mariani, White Pine County, NV
V. Poe, Mineral County, NV
E. Wright, Lincoln County, NV
J. Pitts, Lincoln County, NV
R. Williams, Lander County, NV
J. Hayes, Esmeralda County, NV
M. Hayes, Esmeralda County, NV
B. Mettam, Inyo County, CA
C. Abrams, NRC

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

Bye Stec
Gil Sm
Simmons / Pa
Bianchini L
Brennan H
Giora
Jenetta
Buddison
SAK / Voegele
6/21/91
Crotz

MAY 3 1 1991

Mr. Dwight E. Shelor, Acting Associate Director
for Systems and Compliance
Office of Civilian Radioactive Waste Management
U. S. Department of Energy, RW 30
Washington, D.C. 20585

Dear Mr. Shelor:

SUBJECT: PHASE I REVIEW OF U.S. DEPARTMENT OF ENERGY (DOE) STUDY PLAN FOR CHARACTERIZATION OF THE UNSATURATED-ZONE INFILTRATION

On March 1, 1991, DOE transmitted the study plan entitled "Characterization of the Unsaturated-Zone Infiltration" (Study Plan for Study 8.3.1.17.4.1) to the U.S. Nuclear Regulatory Commission (NRC) for review and comment. NRC has completed its Phase I Review of this document using the Review Plan for NRC Staff Review of DOE Study Plans, Revision 1 (December 6, 1990).

The material submitted in the study plan was considered to be consistent, to the extent possible at this time, with the agreement on content resulting from the NRC-DOE agreements made at the May 7-8, 1986 meeting on Level of Detail for Site Characterization Plans and Study Plans. The NRC staff recognizes that some of the information required in the agreement, especially many of the procedures for field tests and methods for analyses, cannot be provided until the prototype testing described in the study plan is completed. The staff did not consider that the absence of such information compromised its ability to conduct its Phase I Review of the material provided. However, the NRC staff requests that the procedures, methods, and other relevant details be provided to NRC for its review as soon as they are available.

Among the references listed for this study plan are several which have not been provided to NRC and are not readily available in the public domain. We therefore request that DOE provide to us the documents listed in the Enclosure.

A major purpose of the Phase I Review is to identify concerns with studies, tests, or analyses that if started could cause significant and irreparable adverse effects on the site, the site characterization program, or the eventual usability of the data for licensing. Such concerns would constitute <u>objections</u>, as that term has been used in earlier NRC staff reviews of DOE's documents related to site characterization (Consultation Draft Site Characterization Plan and the Site Characterization Plan for the Yucca Mountain site). The Phase I Review of this study plan identified no objections with any of the activities proposed.

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After completion of the Phase I Review, selected study plans are to receive a second level of review, called a Detailed Technical Review, based on the relationship of a given study plan to key site-specific issues or NRC open items, or its reliance on unique, state-of-the-art test or analysis methods. We have decided not to proceed with a Detailed Technical Review of this study plan at this time, in part because the technical details required for such a review will not be available until the prototype studies are completed.

If you have any questions concerning this letter, please contact King Stablein (FTS/[301]-492-0446) of my staff.

Sincerely,

Joseph J. Holonich for

John J. Linehan, Acting Director
Repository Licensing and Quality
  Assurance Project Directorate
Division of High-Level Waste Management
Office of Nuclear Material Safety
  and Safeguards

Enclosure: As Stated

cc: R. Loux, State of Nevada
C. Gertz, DOE/NV
S. Bradhurst, Nye County, NV
M. Baughman, Lincoln County, NV
D. Bechtel, Clark County, NV
D. Weigel, GAO
P. Niedzielski-Eichner, Nye County, NV
C. Thistlethwaite, Inyo County, CA

Enclosure

References for Study Plan 8.3.1.17.4.1 Requested by NRC

- Abrams, M.J., Conel, J.E., and Lang, H.R., 1984, The Joint NASA/GEOSAT Test Case Project--Final Report, Paley, H.N., editor: Tulsa, Oklahoma, American Association of Petroleum Geologists, pt. 2, v. I. Sections 1 and 2, p. 1-1 to 2-24.
- Bouwer, H., 1961, A study of final infiltration rates from cylinder infiltrometers and irrigation furrows with an electrical resistance network: in Trans. Inc. Congr. Soil Sci. 7th, 6:448-456.
- Constantz, J., and Herkelrath, W.N., 1988, Field measurements of the influence of entrapped air upon ponded infiltration rates: Infiltration Principles and Practices, Proceedings International Conference Infiltration Development and Application, January 1988, Honolulu, Hawaii, p. 398-407.
- Firdaouss, M., Maalej, M., and Belin, B., 1983, Identification of the soil thermal diffusivity from the temperature in situ measurements in a semi-arid region: In R.W. Lewis, J.A. Johnson, and W.R. Smith (eds.), Proceedings 3rd International Conference Numerical Methods in Thermal Problems, August 2-5, 1983, Seattle, Wash.
- Flint, A.L. and Childs, S.W., 1987a, Modification of the Priestley-Taylor evaporation equation for soil water limited conditions: In 18th Conference on Agricultrual and Forest Meteorology, W. Lafayette, Indiana, September, 1987, pp. 70-73.
- Hammermeister, D.P., Blout, D.O., and McDaniel, J.C., 1985, Drilling and coring methods that minimize the disturbance of cuttings, core, and rock formation in the unsaturated zone, Yucca Mountain, Nevada: Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose (Unsaturated) Zone: National Water Well Association, p. 507-541.
- Hevesi, J.A., Istok, J.D., and Flint, A.L., 1989a, Precipitation estimation in mountainous terrain using multivariate geostatistical analysis: 1-structural analysis.
- Hevesi, J.A., Flint, A.L., and Istok, J.D., 1989b, Precipitation estimation in mountainous terrain using multivariate geostatistical analysis: 2-applications.
- Kneiblher, C.R.., 1985, Seismic refraction surveys of alluvium-filled washes, Yucca Mountain, Nevada: Reno, Nevada, University of Nevada, Reno, unpublished M.S. thesis, 112 p.

- Morineau, Y., Simandoux, P., and Dupuy, M., 1965, Etude des heterogeneities de permeabilities dans les milieux poreux. Compte Rendu de IIeme Colloque de l'Association de Recherche sur les Techniques de Forge et de Production, Rueil, May 31-June 4:273.

- Reynolds, W.D., and Elrick, D.E., 1985, Measurement of field-saturated hydraulic conductivity, sorptivity and the conductivity-pressure head relationship using the "Guelph Permeameter", in Proceedings, Conference on Characterization and Monitoring of the Vadose Zone, Denver, Colorado, November 1985: National Water Well Association, p. 9-33.

- Scotter, D.R., Clothier, B.E., and Harper, E.R., 1982, Measuring saturated hydraulic conductivity and sorptivity using twin rings: Aust. J. Soil Res. 20:295-304.

- Schmidt, M.R., 1988, Classification of upland soils by geomorphic and physical properties affecting infiltration at Yucca Mountain, Nevada: Golden, Colo., Colorado School of Mines, unpublished M.S. thesis, 116 p.

- Topp, G.C. and Davis, J.L., 1982, Measurement of soil water content using time-domain reflectometry: Canadian Hydrology Symposium: 82, Assoc. Comm. on Hydrology, National Research Council of Canada, Ottawa, p. 269-287.

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

MAY 04 1992

Mr. John P. Roberts, Acting Associate Director
for Systems and Compliance
Office of Civilian Radioactive Waste Management
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, D.C. 20585

Dear Mr. Roberts:

SUBJECT: PHASE I REVIEW OF U.S. DEPARTMENT OF ENERGY STUDY PLAN FOR "WATER RESOURCE ASSESSMENT OF YUCCA MOUNTAIN, NEVADA"

On September 20, 1991, DOE transmitted the study plan, "Water Resource Assessment of Yucca Mountain, Nevada" (Study Plan 8.3.1.9.2.2), to the U.S. Nuclear Regulatory Commission for review and comment. NRC has completed its Phase I Review of this document using the Review Plan for NRC Staff Review of DOE Study Plans, Revision 1 (December 6, 1990).

The material submitted in the study plan was considered to be consistent, to the extent possible at this time, with the NRC-DOE agreement on content of study plans made at the May 7-8, 1986, meeting on Level of Detail for Site Characterization Plans and Study Plans.

Among the references listed for this study plan are several which have not been provided to NRC and are not readily available in the public domain. We therefore request that DOE provide the NRC with the documents which are listed in the Enclosure.

A major purpose of the Phase I Review is to identify concerns with studies, tests, or analyses that, if started, could cause significant and irreparable adverse effects on the site, the site characterization program, or the eventual usability of the data for licensing. Such concerns would constitute objections, as that term has been used in earlier NRC staff reviews of DOE's documents related to site characterization (Consultation Draft Site Characterization Plan and the Site Characterization Plan for the Yucca Mountain Site). It does not appear that the conduct of the activities described in this study plan will have significant adverse impacts on repository performance and the Phase I Review of this study plan identified no objections with any of the activities proposed.

After completion of the Phase I Review, selected study plans are to receive a second level of review, called a Detailed Technical Review, based on the relationship of a given study plan to key site-specific issues or NRC open items, or its reliance on unique, state-of-the-art test or analysis methods. We have decided not to proceed with a Detailed Technical Review of this study plan.

However, there is one concern that the NRC staff has. On page 1-1 of the plan, it is stated that groundwater is the only resource expected to have the potential for future inadvertent human intrusion. This statement is premature given that Yucca Mountain is located in a geologic setting that includes current gold production and exploration for hydrocarbon resources. For example, five new mines and prospects have been located within 48 km of the

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ENCLOSURE 2

proposed Yucca Mountain site between January 1988 and July 1990 (Raney, 1990)[1]. Recent oil exploration has occurred within 25 km of the proposed site (State of Nevada, 1990)[2]. Based on the information provided in the Site Characterization Plan, the potential for these resources to occur at the site will be addressed as part of Study Plan 8.3.1.9.2.1 (natural resource assessment). We are concerned that this early conclusion concerning water resources may impact the work being planned with respect to the natural resources assessment study plan.

If you have any questions concerning this letter, please contact Charlotte Abrams (FTS 964-3403, 301-504-3403) of my staff.

Sincerely,

Joseph J. Holonich

Joseph J. Holonich, Director
Repository Licensing and Quality
Assurance Project Directorate
Division of High-Level Waste Management
Office of Nuclear Material Safety
and Safeguards

Enclosure: As stated

cc: R. Loux, State of Nevada
C. Gertz, DOE/NV
S. Bradhurst, Nye County, NV
M. Baughman, Lincoln County, NV
D. Bechtel, Clark County, NV
D. Weigel, GAO
P. Niedzielski-Eichner, Nye County, NV
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P. Goicoechea, Eureka County, NV
L. Vaughan II, Esmeralda County, NV
C. Shank, Churchill County, NV
T. J. Hickey, Nevada Legislative Committee

---

[1] Raney, R.G., 1990, Active mines and prospects within a thirty-mile radius of the proposed high-level repository site at Yucca Mountain, Nye County, Nevada, subsequent to January 1988: U.S. Bureau of Mines, NRC FIN D1018.

[2] State of Nevada, 1990, Oil and gas permit notices: State of Nevada, Department of Minerals, Permit Numbers 605-607, issued December 14, 1990.

References:

DeGabriele, C.D. and C.L. Wu. 1987. Water Requirements, Bechtel National, Inc., for Sandia National Laboratory, 52-9817.

Gibbons, D.C., 1986. The Economic Value of Water, Resources of the Future, Washington, D.C.

Gollnick, C.A., 1988. Irrigation Study. Valley Electric Association, Pahrump, Nev.

ENCLOSURE

THIS PAGE IS AN OVERSIZED DRAWING OR FIGURE,

THAT CAN BE VIEWED AT THE RECORD TITLED: PLATE 1: GENESIS-LITHOLOGY-QUALIFIER MAP OF A WASH/RIDGE SYSTEM, YUCCA MOUNTAIN, NEVADA

WITHIN THIS PACKAGE...OR, BY SEARCHING USING THE DRAWING NUMBER: PLATE 1

NOTE: Because of this page's large file size, it may be more convenient to copy the file to a local drive and use the Imaging (Wang) viewer, which can be accessed from the Programs/Accessories menu.

THIS PAGE IS AN OVERSIZED DRAWING OR FIGURE,

THAT CAN BE VIEWED AT THE RECORD TITLED:

PLATE 2:

SAMPLE STATION LOCATIONS

WITHIN THIS PACKAGE...OR, BY SEARCHING USING THE DRAWING NUMBER:

PLATE 2

NOTE: Because of this page's large file size, it may be more convenient to copy the file to a local drive and use the Imaging (Wang) viewer, which can be accessed from the Programs/Accessories menu.

rec'd with letter
Md - 9/16/92

U.S. DEPARTMENT OF ENERGY

OCRWM

YUCCA MOUNTAIN

YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT

REFERENCES FOR STUDY PLAN 8.3.1.2.2.1

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Enclosure 3
8.3.1.2.2.1

Enclosure

References for Study Plan 8.3.1.~~17.4.1~~ 2.2.1 Requested by NRC

- Abrams, M.J., Conel, J.E., and Lang, H.R., 1984, The Joint NASA/GEOSAT Test Case Project--Final Report, Paley, H.N., editor: Tulsa, Oklahoma, American Association of Petroleum Geologists, pt. 2, v. I. Sections 1 and 2, p. 1-1 to 2-24.
- Bouwer, H., 1961, A study of final infiltration rates from cylinder infiltrometers and irrigation furrows with an electrical resistance network: <u>in</u> Trans. Inc. Congr. Soil Sci. 7th, 6:448-456.
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- Hammermeister, D.P., Blout, D.O., and McDaniel, J.C., 1985, Drilling and coring methods that minimize the disturbance of cuttings, core, and rock formation in the unsaturated zone, Yucca Mountain, Nevada: Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose (Unsaturated) Zone: National Water Well Association, p. 507-541.
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- Hevesi, J.A., Flint, A.L., and Istok, J.D., 1989b, Precipitation estimation in mountainous terrain using multivariate geostatistical analysis: 2-applications.
- Kneiblher, C.R.., 1985, Seismic refraction surveys of alluvium-filled washes, Yucca Mountain, Nevada: Reno, Nevada, University of Nevada, Reno, unpublished M.S. thesis, 112 p.

8.3.1.2.2.1

Enclosure 3

- o Morineau, Y., Simandoux, P., and Dupuy, M., 1965, Etude des heterogeneities de permeabilities dans les milieux poreux. Compte Rendu de Ileme Colloque de l'Association de Recherche sur les Techniques de Forge et de Production, Rueil, May 31-June 4:273.

- o Reynolds, W.D., and Elrick, D.E., 1985, Measurement of field-saturated hydraulic conductivity, sorptivity and the conductivity-pressure head relationship using the "Guelph Permeameter", in Proceedings, Conference on Characterization and Monitoring of the Vadose Zone, Denver, Colorado, November 1985: National Water Well Association, p. 9-33.

- o Scotter, D.R., Clothier, B.E., and Harper, E.R., 1982, Measuring saturated hydraulic conductivity and sorptivity using twin rings: Aust. J. Soil Res. 20:295-304.

- o Schmidt, M.R., 1988, Classification of upland soils by geomorphic and physical properties affecting infiltration at Yucca Mountain, Nevada: Golden, Colo., Colorado School of Mines, unpublished M.S. thesis, 116 p.

- o Topp, G.C. and Davis, J.L., 1982, Measurement of soil water content using time-domain reflectometry: Canadian Hydrology Symposium: 82, Assoc. Comm. on Hydrology, National Research Council of Canada, Ottawa, p. 269-287.

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Reprinted from the Preprint Volume, of the 18th Conference on Agricultural and Forest Meteorology and 8th Conference on Biometeorology and Aerobiology, Sept. 14-18, 1987. W. Lafayette, Ind. Published by the American Meteorological Society, Boston, Mass.

MODIFICATION OF THE PRIESTLEY-TAYLOR EVAPORATION EQUATION FOR SOIL WATER LIMITED CONDITIONS

Alan L. Flint and Stuart W. Childs

U.S. Geological Survey
Mercury, Nevada
and
Oregon State University
Corvallis, Oregon

1. INTRODUCTION

A major limitation of many reforestation sites is a lack of water during the growing season. In areas with xeric climates, this is often combined with high temperatures which act to increase plant stress. Any assessment of the harshness of reforestation sites requires information regarding both water supply and environmental demand. The measurement and evaluation of a surface energy budget is a useful analytical approach because components of both the heat and water environments are included. This approach does, however, require detailed, site specific measurements.

A number of simplifications of energy budget techniques have been used to decrease the quantity and intensity of measurements required. The Penman equation (Penman, 1948) is commonly used in situations where detailed data are available. The simplifications used to model the aerodynamic parts of the equation make the equation useful only for calculation of potential evapotranspiration. Furthermore, the equation requires calibration. The Penman-Monteith equation (Monteith, 1966) allows calculation of actual evapotranspiration but requires detailed knowledge about the resistance to heat and water flow at the evaporating surface. Priestley and Taylor (1972) suggested a modification of the Penman equation which requires less extensive measurements:

$$\lambda E_p = \alpha \cdot \frac{s}{s + \gamma} \cdot (Q^* - G) \qquad (1)$$

where λE_p is potential evapotranspiration, α is a model coefficient, s is the slope of the saturation vapor density curve, γ is the psychrometric constant, Q^* is net radiation and G is soil heat flux. In this formulation the aerodynamic term is modeled as $(\alpha - 1) \cdot [s/(s+\gamma)] \cdot (Q^* - G)$. This simplification is successful because the radiation term generally dominates the aerodynamic term (Stewart, 1983).

The coefficient α for daily calculations is 1.26 for freely evaporating surfaces (Priestley and Taylor, 1972; Stewart and Rouse, 1977). α depends on surface vegetation and microclimatic conditions and ranges from 1.57 for conditions of strong advection to 0.72 for forest conditions (Table 1).

Table 1. Measured values of the Priestley-Taylor coefficient, α.

α	Surface conditions	Reference
1.57	Strongly advective conditions	Jury & Tanner, 1975
1.29	Grass (soil at field capacity)	Mukammal & Neumann, 1977
1.27	Irrigated ryegrass	Davies & Allen, 1972
1.26	Saturated surface	Priestley & Taylor, 1972
1.26	Open water surface	Priestley & Taylor, 1972
1.26	Wet meadow	Stewart & Rouse, 1977
1.18	Wet Douglas-fir forest	McNaughton & Black, 1973
1.12	Short grass	DeBruin & Holtslag, 1982
1.05	Douglas-fir forest	McNaughton & Black, 1973
1.04	Bare soil surface	Barton, 1979
0.84	Douglas-fir forest Unthinned	Black, 1979
0.80	Douglas-fir forest Thinned	Black, 1979
0.73	Douglas-fir forest (Daytime)	Giles et al., 1984
0.72	Spruce forest (Daytime)	Shuttleworth & Calder, 1979

Although the value of α for moist surface conditions (α>1) may be a function of wind speed and aerodynamic resistance, under drier conditions (α<1) it is related to surface resistance (De Bruin, 1983). Actual evapotranspiration under dry conditions is lower than potential and depends on soil water status, exchange surface properties and environmental demand (Black, 1979; De Bruin, 1983; Priestley and Taylor, 1972; Tanner and Jury, 1975).

Methods involving calculation of surface resistance have generally been based on the Penman-Monteith equation. Use of the Priestley-Taylor equation for calculation of actual evapotranspiration has involved empirical relationships to soil water content. Often, α is redefined to be a function of soil water content (Mukammal and Neumann, 1977, Davies and Allen, 1972, Barton, 1979). Another approach is to define a soil water content below which evapotranspiration is limited and the Priestley-Taylor equation is in error. This value would vary

Enclosure 3
8.3.1.2.2.1

greatly with soil type, vegetation and environmental demand but covers a much smaller range when expressed as a percentage of total "available" soil water (Table 2). For vegetated surfaces, 50 to 80 percent of the "available" soil water can be extracted at the potential rate. Bare soil evaporation was limited when 40 percent of the available water was removed. This result is not unexpected (Tanner and Jury, 1976).

2. OBJECTIVE AND APPROACH

The objective of this research was to calibrate the modified Priestley-Taylor equation for soil water limited conditions. This was done by redefining the coefficient, α, to be a function of soil water content (α'). Since soil water status changes with depth, we also examined the relationship between α' and soil water content at different depths. Although the original approach of Priestley and Taylor was to apply their formulation to large scale environments, we apply the modified version to a small forest clearcut.

Table 2. Percentage reduction in "available" water (R_c) before evapotranspiration is limited.

R_c	Surface conditions	Reference
82	Douglas-fir forest (Low Demand)	Black & Spittlehouse, 1980
81	Lysimeter and bean crop	Priestley & Taylor, 1972
77	Lysimeter and field crop	Priestley & Taylor, 1972
75	Lysimeter and grass cover	Mukammal & Neumann, 1977
66	Douglas-fir forest (High Demand)	Black & Spittlehouse, 1980
60	Douglas-fir forest	Black, 1979
60	Forest clearcut	Figure 3, this paper
55	Cropped surface	Davies & Allen, 1972
50	Lysimeter and pasture crop	Priestley & Taylor, 1972
40	Bare soil surface	Estimate from Barton, 1979

3. METHODS

3.1 Field Methods

Data for this study were obtained during a reforestation field experiment in southwest Oregon [see Flint and Childs (1987) for complete details]. The site had a southerly exposure, a shallow, rocky soil and 81 percent vegetation cover. Measurements of soil water content and temperature were made at ten locations and averaged for the site. Data were collected on ten dates between April and September, 1983. Soil water content was measured using a two probe gamma attenuation device (Model 2376, Troxler Labs, Research Triangle Park, NC) in 0.025 m depth intervals.

Soil temperatures were measured at five depths (0.02, 0.04, 0.08, 0.16, 0.32 m) using five thermistors (YSI #44202, Yellow Springs Instruments, Yellow Springs, OH) in a plastic probe. Data were integrated for 15 minutes and stored in a data logger (Model CR-5, Campbell Scientific Inc., Logan, UT). Temperature data and soil heat capacities calculated from soil density and water content were used to calculate soil heat flux using a calorimetric technique (Fuchs, 1986).

Air temperatures were measured at 0.2 m and 2.0 m using thermistors (YSI #44202) mounted in radiation shields. Dew point temperatures were measured at 0.2 and 2.0 m using LiCl dewcells (Holbo, 1981). Net radiation was measured using a miniature all-wave net radiometer (C. W. Thornthwaite Assoc., Camden, NJ). Sensor output was read every 10 seconds, integrated for 30 minutes and stored [using a Model CR-21 datalogger (Campbell Scientific Inc., Logan, UT)].

3.2 Modeling Procedure

Actual evaporation was calculated hourly using the Bowen ratio method:

$$\lambda E_a = \frac{(Q^* - G)}{1 + \beta} \tag{2}$$

where β, the Bowen ratio, is the ratio of sensible to latent heat flux. β is calculated as:

$$\beta = \frac{\rho C_p (T_1 - T_2)}{\lambda(\rho_1 - \rho_2)} \tag{3}$$

where ρC_p is the volumetric heat capacity of air, λ is the latent heat of vaporization, T_1 and T_2 are air temperatures at two heights, ρ_1 and ρ_2 are water vapor density at the same heights.

The Priestley-Taylor equation (Eq. 1) was modified by replacing λE_p and α with λE_a and α' and solving for α':

$$\alpha' = \frac{\lambda E_a}{\frac{s}{s+\gamma} \cdot (Q^* - G)} \tag{4}$$

Although the coefficient α' could be related to any process that limits evapotranspiration (e.g. soil hydraulic resistance, aerodynamic resistance, stomatal resistance), we chose to relate α' to soil water status in a manner similar to Davies and Allen (1973) and Barton (1979):

$$\alpha' = A[1 - \exp(-B \frac{\theta}{\theta_s})] \tag{5}$$

where A and B are regression coefficients and θ/θ_s is the current volumetric soil water content divided by the value at saturation. Davies and Allen (1972) used soil water content divided by soil water content at field capacity (θ/θ_{fc}) while Barton (1979) simply used gravimetric water content without any scaling. In Eq. 5 the coefficient A approaches the Priestley-Taylor coefficient (α) as the soil moisture content approaches saturation.

4. RESULTS AND DISCUSSION

One of the ten diurnal data sets analyzed is shown in Figure 1. The measured values (Bowen ratio) and the modeled data (modified Priestley-Taylor equation with daily average α') are in close agreement at midday. The apparent error in measured values of λE_a occurs when the Bowen ratio (β) is near -1 (0700, 1800 and 1900 hours, Figure 2). In order to avoid the large variation in α' calculated when the Bowen ratio method is unstable (Jury and Tanner, 1975), daily average values of α' were calculated using midday values of α' when $\beta > 0$. The magnitude of error associated with applying the midday average of α' to early and late periods of the day is small because the value of (Q^*-G) is small. The Bowen ratio technique could also be improved by smoothing or averaging β. We preferred, however, to use the Priestley-Taylor equation because of the smaller data requirements.

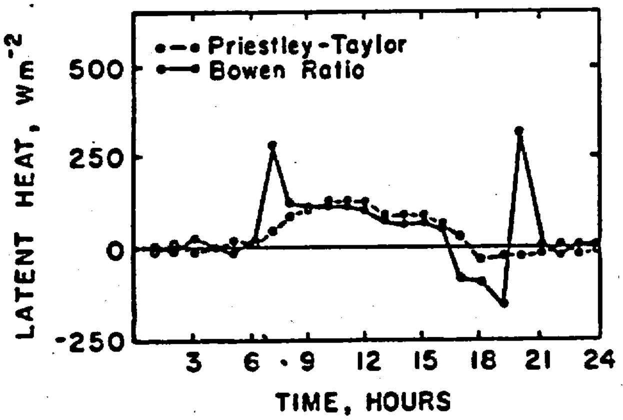

Figure 1. Results of latent heat flux using the Bowen ratio technique and the Priestley-Taylor technique with the daytime average value of the modified Priestley-Taylor coefficient α' for August 12, 1983. (α'=0.55).

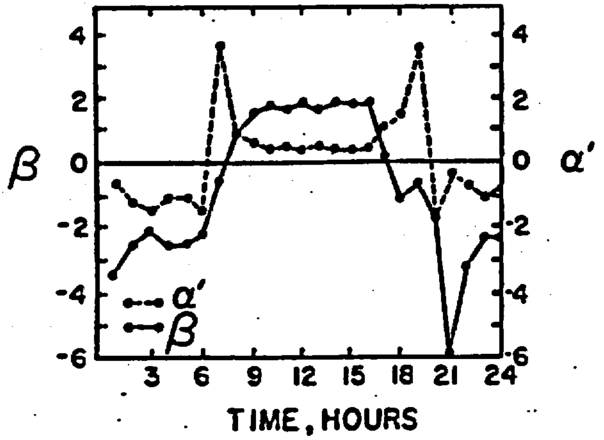

Figure 2. Values for the Bowen ratio (β) and for the ratio of latent heat (λE) to $(s/s+\gamma)\cdot(Q^*-G)$ which is equated to the Priestley-Taylor coefficient α' for nonsaturated conditions.

The regression coefficients A and B in Eq. 5 were estimated using nonlinear regression of α' against θ/θ_s. The values for θ and θ_s were determined for five different total soil profile depth increments (Table 3).

Table 3. Results of a series of regressions between α' and θ/θ_s (Eq. 5). SSQ is the error sum of squares.

	----- θ/θ_s -----		
Depth (m)	A	B	SSQ
All data points			
0-0.1	1.08	-4.06	0.1178
0-0.2	1.09	-4.20	0.1243
0-0.3	1.18	-3.41	0.1017
0-0.4	1.17	-3.38	0.0922
0-0.5	1.27	-2.83	0.0831
	----- θ/θ_s -----		
Depth (m)	A	B	SSQ
All data points where $Q^* > 12$ MJ m^{-2}			
0-0.1	0.89	-6.30	0.0559
0-0.2	0.88	-6.63	0.0642
0-0.3	0.93	-5.42	0.0490
0-0.4	0.96	-4.82	0.0378
0-0.5	1.00	-4.18	0.0371

The effect of depth of water content measurement on regression results showed distinct trends. Increased profile depth reduced the error sum of squares (SSQ) in the regressions. The coefficient A, which should approximate the Priestley-Taylor coefficient (α) ranges from 1.08 to 1.27 as the soil thickness goes from 0.1 to 0.5 m. This large variation is within the range commonly measured (Table 1) but the sensitivity of this value to depth of measurement of soil water content discourages attaching any significance to the value of A.

The relationship of α' to soil water content is given in Figure 3 for a profile depth of 0.50 m. The regression fits the data well except at higher soil water contents. One of these outlier points represents a day with low environmental demand. Black (1979) suggested that it may be inappropriate to use the modified Priestley-Taylor approach on such days because even soils with low water content can supply enough water for potential evapotranspiration. We reanalyzed our data excluding values with a total radiation load of <12 MJ m^{-2} day^{-1} (one data point is noted in Figure 3). The resulting values of A (0.89 to 1.00 over the depth range, Table 4) were similar to the values of α found by Black (1979, Table 1). Excluding the one data point <12 MJ m^{-2} day^{-1}, would yield an estimate of A = 0.85 when the soil is near field capacity (θ/θ_s = 0.6).

A simplified formulation of α' would be to set an upper limit of α' = 0.85 where λE_p =

λE_a. α' could be reduced when soil water content falls below some critical value of θ/θ_s where soil water supply limits evapotranspiration. By estimating total available water content as the difference between field capacity ($\theta/\theta_s = 0.60$) and driest seasonal water content ($\theta/\theta_s = 0.18$) it can be seen that when more than 60 percent of this total available water is used, ($\theta/\theta_s = 0.35$, Figure 3), soil water becomes limiting. This value is in general agreement with the data in Table 2. Although further analysis is needed to properly evaluate α' when the soil is at field capacity for our soil, the relationship between α' and θ/θ_s below field capacity would remain the same.

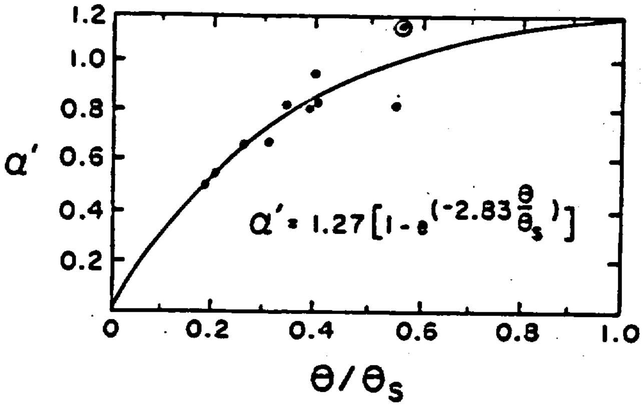

Figure 3. Modified Priestley-Taylor coefficient α' versus percentage of saturation (θ/θ_s, 0-0.5 m). The circled point indicates data for a day with $Q^* < 12$ MJ m^{-2} day^{-1}.

5. CONCLUSIONS

The Priestley-Taylor equation can be used to calculate actual evaporation by incorporating α', a variable dependent on soil water content. The relationship to soil water content is exponential. The coefficients A and B depend on the depth of measurement for soil water content and the environmental demand. The best results for our data were achieved when soil water content was averaged from the surface to 0.50 m and any data point with total radiation less than 12 MJ m^{-2} day^{-1} was excluded.

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IDENTIFICATION OF THE SOIL THERMAL DIFFUSIVITY FROM THE TEMPERATURE IN SITU MEASUREMENTS IN A SEMI-ARID REGION

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ABSTRACT

The purpose of this study is to predict the apparent thermal diffusivity of the soil from the temperature in situ measurements. It can be determined as a constant from an analytical approach based on Fourier analysis, or as varying with the soil temperature by a numerical identification. The results of numerical resolution of the heat diffusion equation utilizing different values of the diffusivity are compared to the observed temperatures. We note that the smaller differences are obtained when the diffusivity used for computations varies as a second order polynomial function of temperature. In all the cases the mean relative absolute difference doesn't exceed 0.33°C (1.14%). This confirms that the diffusion-based heat flow model gives quite acceptable simulations of the soil temperature.

INTRODUCTION

In the hot summer soil temperature becomes too high and this greatly affects the growth of roots of plants and microorganisms living in the soil. The daily differences between maximum and minimum values of the soil temperature near the surface are about 30°C. Knowledge of the thermal and hydraulic characteristics of the soil plays an important role in the determination of the rate of evaporation of water, which is a rare element especially in arid regions. In this study we have taken into consideration the thermal characteristics related to this problem.

The temperatures of the natural soil in southern Tunisia had been measured at different depths below the surface and recorded at 3 min intervals during five different time period of a year. This soil is practically a homogeneous mixture of muddy sands down to a depth of 1 m. We show that the prediction of the thermal characteristics of the soil is possible from the

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Enclosure 3

in situ measurements of the soil temperature either by an analytical approach based on Fourier analysis, or by a numerical identification on polynomial forms.

FOURIER ANALYSIS

The 1D heat conduction in the soil is modelled with the equation

$$\rho\, c(T)\, \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\{\lambda(T)\, \frac{\partial T}{\partial z}\} \qquad (1)$$

where: T is temperature in K, c is the specific heat capacity ($J\ K^{-1}\ g^{-1}$), ρ is the density ($g\ m^{-3}$), λ is the thermal conductivity ($W\ m^{-1}K^{-1}$), z is depth (m), t is time (sec).

If we consider the variation with respect to the temperature of the heat capacity c(T) and thermal conductivity $\lambda(T)$ negligeable, and by introducing the thermal diffusivity $a = \lambda/\rho c$ equation (1) can be rewritten as :

$$\frac{\partial T}{\partial t} = a\, \frac{\partial^2 T}{\partial z^2} \qquad (2)$$

If we suppose that the boundary condition near the surface of the soil to be of the forme :

$$T(z_o,t) = T_a(z_o) + \sum_{k=1}^{\infty} A_k(z_o).\cos\{k\omega t - \phi_k(z_o)\} \qquad (3)$$

and at the bottom as :

$$T \to T_\infty \quad \text{when} \quad z \to \infty \qquad (4)$$

The soil temperature can be approximated analytically in a Fourier series as below :

$$T(z,t) = T_a(z) + \sum_{k=1}^{\infty} A_k(z_o).\exp\{-(z-z_o)/D\}.\cos\{k\omega t-(z-z_o)/D - \phi_k(z_o)\} \qquad (5)$$

the constant D is called the damping depth. It is related to the thermal diffusivity of the soil and the frequency of the variations as follows :

$$D = \sqrt{2a/k\omega} \qquad (6)$$

In Eq. 5, $A_k(z) = A_k(z_o).\exp\{-(z-z_o)/D\}$ represents the amplitude of the soil temperature of an order of magnitude k, and $\phi_k(z) = (z-z_o)/D + \phi_k(z_o)$ is the corresponding phase shift.

The table 1 presents the temperature amplitudes and phase shifts of the first and second order. The devlopment is restricted to the second order because the amplitude of the third order are rather negligeable. The decrease of the amplitude with depth and the increasing phase lag are typical for the propagation of the periodic temperature variation in a soil. At a depth $z=16.2$ cm, the amplitude (first order) is 0.18 times the amplitude at $z=1$cm; it is only about $0.06A_1(z_o)$ at $z=30$cm.

This confirms that the diurnal variation does not penetrates below 50 cm.

		first order		second order	
z, cm	$T_a(z)$, °C	$A_1(z)$, °C	$\phi_1(z)$, rd	$A_2(z)$, °C	$\phi_2(z)$, rd
1.0	29.11	11.78	3.593	3.98	0.834
2.3	28.98	10.09	3.719	3.24	1.011
4.2	28.63	7.82	3.922	2.31	1.275
8.3	28.10	4.70	4.349	1.78	1.810
16.2	27.41	2.12	5.105	0.38	2.896
30.0	26.71	0.77	6.110	0.102	4.347
100.0	24.96	0.12	12.532	0.008	8.284

Table 1 : Values of the mean soil temperature, the amplitudes and the phase shifts of the first and second order, at different depths

The mean thermal diffusivity of the soil is obtained by a linear regression of the curves $\mathrm{Log}\{A_k(z)/A_k(z_o)\} = F(z)$ and $\phi_k(z)-\phi_k(z_o) = G(z)$. The diffusivities determined with respect to the amplitudes are :

$$a(A_1) = 10.492\ \mathrm{cm}^2/\mathrm{h} \quad \text{for the first order}$$

$$\text{and } a(A_2) = 11.181\ \mathrm{cm}^2/\mathrm{h} \quad \text{for the second order}$$

With respect to the phase shifts they are given by :

$$a(\phi_1) = 13.260\ \mathrm{cm}^2/\mathrm{h} \quad \text{for the first order}$$

$$\text{and } a(\phi_2) = 14.394\ \mathrm{cm}^2/\mathrm{h} \quad \text{for the second order}$$

The diffusivities are relatively the same whether they are calculated with the first or second order. But these values are rather different when calculated with the phase shifts and this is 25 % more important than that obtained from the amplitudes.

NUMERICAL SIMULATION

The direct problem (Eq. 2) is then solved numerically by an implicit scheme utilizing the values of diffusivity. The observed temperatures at the depth of 1 cm and 100 cm are taken respectively as the upper and the lower boundary conditions. The time step is taken to be 15 min and the space discretization is variable.

The results are compared to the observed temperatures as can be shown in the Figures 1 and 2 at depths of 2.3 cm, 4.2, 8.3, 16.2, and 30 cm. The differences are initially zero (at t=0h), increase around noon, and decrease again after the soil temperature in a given depth reaches its maximum, and are negligeable at the end of the cycle (t=24h).

The effect of soil diffusivity used to solve numerically Eq. 2 is shown by comparisons between Figs. 1 and 2. The

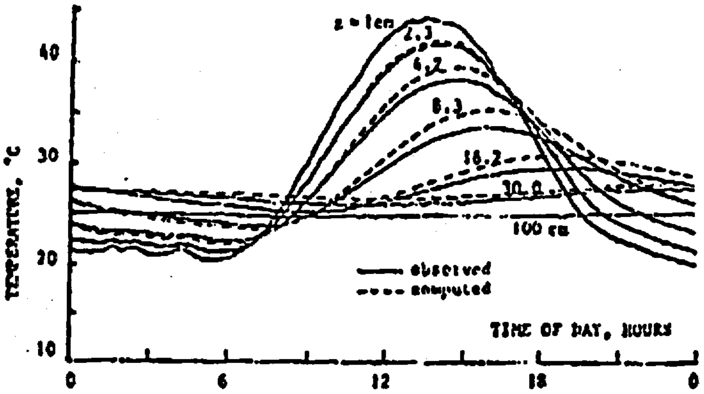

Figure 1 : Comparison of the observed soil temperature and the computed one using the diffusivity determined by the phase shifts

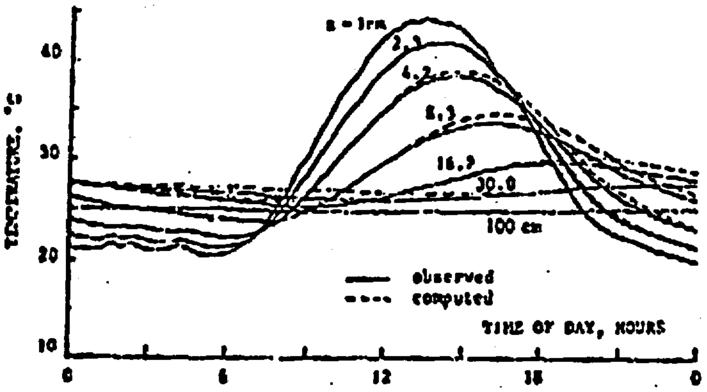

Figure 2 : Comparison of the observed soil temperature and the computed one using the diffusivity determined by the amplitudes

differences are quite smaller when the diffusivity is determined from the amplitudes ($a=10.49 cm^2/h$) than when it is determined from the phase shifts ($a=13.26 cm^2/h$).

In the table 2 are given the maximum values of the absolute differences between the observed and the computed soil temperature. The corresponding relative values (%), the absolute mean differences and their relative values are equally presented.

	maximum absolute difference	maximum relative difference	mean absolute difference	mean relative difference
$a(\phi_1)=13.26$	1.63 °C	4.87 %	0.330 °C	1.141 %
$a(A_1)=10.49$	1.08 °C	3.35 %	0.275 °C	0.982 %

Table 2 : Values of the maximum or mean, absolute or relative differences between the observed soil temperature and the computed one using the diffusivity determined by the phase shifts $a_{(\phi_1)}$ or by the amplitudes $a_{(A_1)}$

The mean relative differences are about 1 % and are of the same order as the experimental error induced by the thermocouples (±0.5 %).

NUMERICAL IDENTIFICATION

By minimizing the differences between experimental results and those obtained by numerical resolution of Eq. 1 it is possible to identify the apparent diffusivity of the soil knowing the thermal profiles at differnet instants of the cycle. The water content of the soil is supposed to be known, then it is possible to calculate at each instant the specific heat for different depths. This problem then leads to identification of the apparent thermal conductivity of the soil which can be determined from the following equation :

$$\rho . c(z,t) \cdot \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \{ \lambda(T) \frac{\partial T}{\partial z} \} \qquad (7)$$

and we search the value of $\tilde{\lambda}$ which minimizes the following function :

$$f(\tilde{\lambda}) = \sum_n \left[\sum_i \left| \frac{\{\tilde{T}_i^n(\tilde{\lambda})\}^2 - \{T_i^n\}^2}{(T_i^n)^2} \right| \right] \qquad (8)$$

where T_i^n is the experimental value of the soil temperature at any point z_i and at any instant t_n of the cycle, $\tilde{T}_i^n(\tilde{\lambda})$ is the temperature computed with $\tilde{\lambda}$ and corresponds to the same point.

Moreover, we assume that

$$\left| \tilde{T}_i^n(\tilde{\lambda}) - T_i^n \right| \rightarrow 0 \quad \forall\, i,n \qquad (9)$$

and $\lambda_{min} \leqslant \tilde{\lambda}(T) \leqslant \lambda_{max} \quad \forall\, T$ defined as $T_{min} \leqslant T \leqslant T_{max}$.

$\tilde{\lambda}$ is expressed as a polynomial function of T as :

$$\tilde{\lambda}(T) = \sum_i a_i T^{bi} \qquad (9)$$

The initial estimation of $\tilde{\lambda}$ is that obtained from the analytical solution. The numerical identification utilizes a sequential augmented lagrangian method. The minimization problem is solved by a newton method.

We show in figure 3 the variations of the apparent thermal diffusivity function of the temperature. These diffusivities are supposed to be of the form : $a=cte$, $a(T)=A+B.T$, $a(T)=A+B.T+C.T^2$, $a(T)=A+B.T^{\alpha}$, valuables for $20\,°C \leqslant T \leqslant 44\,°C$. We note that the diffusivity determined by numerical identification as a constant is close to the value determined analytically from the amplitudes.

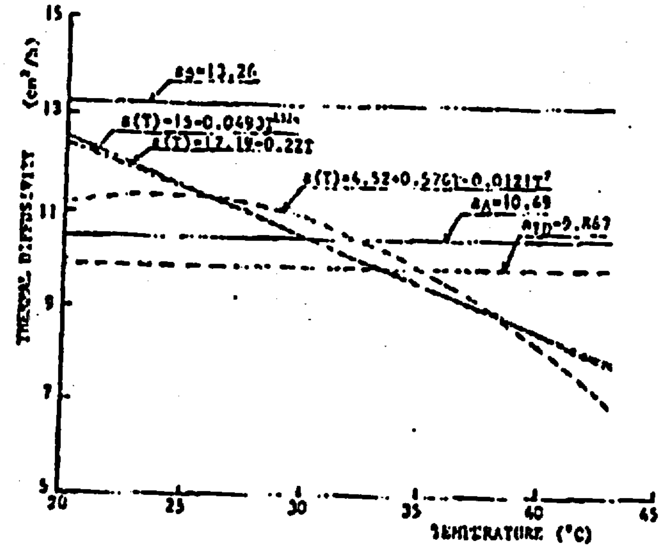

Figure 3 : Variation of the apparent thermal diffusivity of the soil as a function of the temperature

COMPARISON OF THE RESULTS

In figures 4, 5, 6, 7 the experimental results are compared at different depths to the results of numerical solution of the direct problem (Eq. 4) utilizing the diffusivity expressed by different polynomial forms. We note that the differences are the smaller when the diffusivity is assumed to vary with temperature. In this case appear successively under-estimations and over-estimations of the temperature when time increases. Remember that when the diffusivities are assumed to be constant (Figs. 1, 2, 4), the computed temperatures are always more important than the observed.

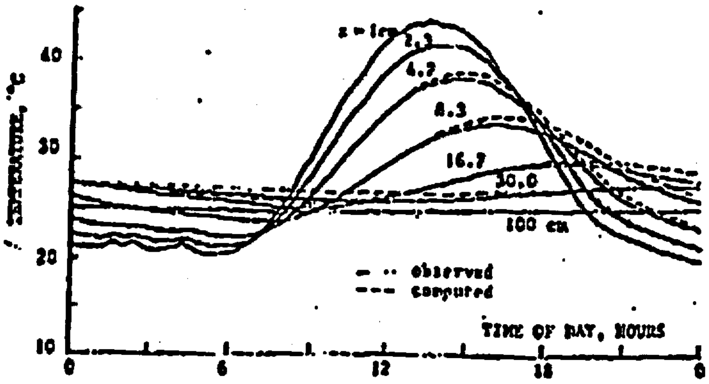

Figure 4 : Comparison of the observed soil temperature and the computed one using the diffusivity determined by numerical identification as a constante

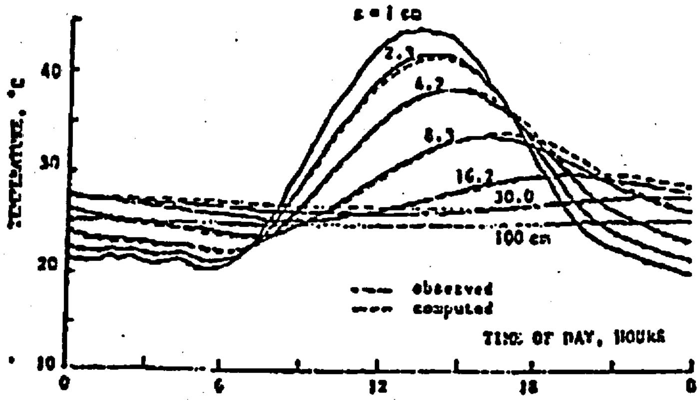

Figure 5 : Comparison of the observed soil temperature and the computed one using the diffusivity determined by numerical identification as : $a(T) = A + B.T$

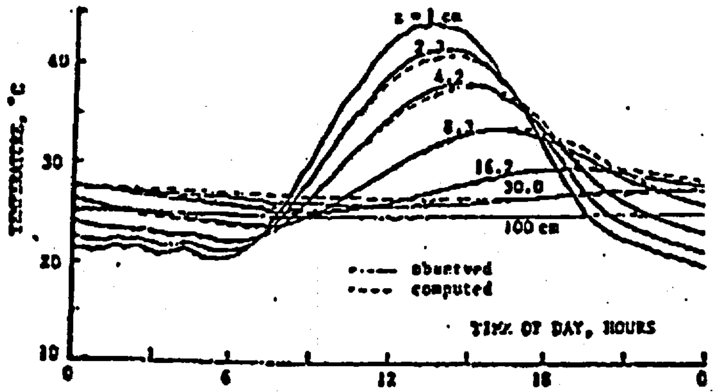

Figure 6 : Comparison of the observed soil temperature and the computed one using the diffusivity determined by numerical identification as : $a(T) = A + B.T + C.T^2$

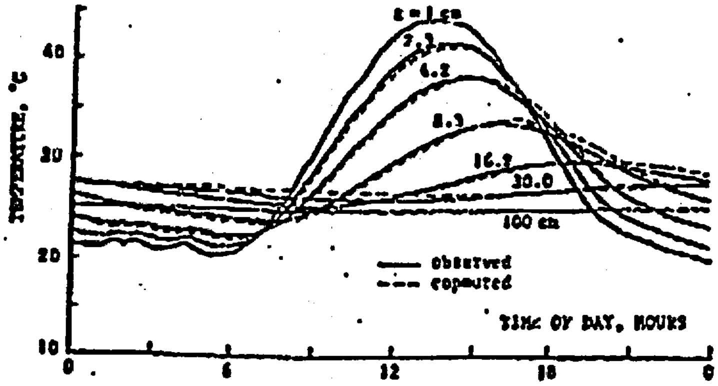

Figure 7 : Comparison of the observed soil temperature and the computed one using the diffusivity determined by numerical identification as : $a(T) = A + B.T^{\alpha}$

Finally we show in table 3, when the diffusivities are determined by numerical identification, the same differences as in table 2. One notes that the absolute mean difference obtained with the polynomial of the second order is 0.22 °C, and is 1.5 times smaller than in case of diffusivity determined from the phase shifts (0.33 °C).

	maximum absolute difference	maximum relative difference	mean absolute difference	mean relative difference
$a = cte$	1.09 °C	3.47 %	0.281 °C	1.01 %
$a(T)=A+B.T$	0.80 °C	2.54 %	0.228 °C	0.832 %
$a(T)=A+B.T+C.T^2$	0.73 °C	2.33 %	0.220 °C	0.796 %
$a(T)=A+B.T^{\alpha}$	0.79 °C	2.53 %	0.227 °C	0.828 %

Table 3 : Values of the maximum or mean, absolute or relative differences between the observed soil temperature and the computed one using the diffusivity determined by a numerical identification.

CONCLUSION

In the present work we propose a numerical method to identify the apparent thermal diffusivity of a soil from the experimental field temperature. The diffusivity can be determined either as a constant or varying with temperature. The differences between the observed and the computed temperatures are small, and are of the same order as the experimental error induced by the thermocouples.

The diffusivity which induces the smaller errors seams to be the second order polynomial as $a(T)=4.52+0.576T-0.0121T^2$. The mean absolute difference is in this case found to be 0.22°C and the absolute difference does not exeed 0.7°C in a maximum.

The proposed method was tested on one day cycle and will be applicated to other daily cycles. Now it seams possible that this analysis can be extended to other type of soils, which contains water and where the hydraulic non linearities will be preponderants.

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