A N N U A L   R E P O R T

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U. S. WATER CONSERVATION LABORATORY
Agricultural Research Service
U. S. Department of Agriculture
Western Region
4331 East Broadway
Phoenix, Arizona 85040

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Personnel (continued)

Temporary Employees:

Anderson, Michael G.	Student Aide
Brooks, George	Student Aide
Carney, Brian	Student Aide
Clemm, Nancy E.	Engineering Aide
DeJuan, Jacinto	Engineering Technician
Estrada, A. J.	Electronic Technician
Gill, Cauleen	Work Study (Clerical)
Gommel, Joel L.	Machinist
Harper, James R.	Electronic Technician
Jacobs, John S.	Electronic Technician
Jimenez, Leonardo	Engineering Draftsman
Jimenez, Ricardo	Engineering Draftsman
Libertouski, Antony C.	Biological Aide
Nieto, Santos	Electronic Technician
Otterson, Scott	Biological Aide
Quinton, Sherri	Work Study (Clerical)
Renner, Rick	Biological Aide
Scott, La Verne	Work Study (Clerical)
Szabo, Richard	Electronic Technician
Tyrrel, Jerry	Physical Science Technician
Yermasek, Kathy	Work Study (Clerical)

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PERSONNEL

The laboratory staff is as follows:

<u>Permanent Employees:</u>

Allen, Robert F.	Electronics Engineer
Auer, Gladys C.	Physical Science Technician
Bell, Frieda L.	Clerk-Typist
Bouwer, Herman	Research Hydraulic Engineer, Research Leader and Laboratory Director
Bucks, Dale A.	Agricultural Engineer
Celaya, L. Susan	Clerk-Typist
Clayton, Yvonne W.	Clerk-Typist (resigned August)
Clemmens, Albert J.	Research Hydraulic Engineer
Dedrick, Allen R.	Agricultural Engineer
Ehrler, William L.	Plant Physiologist
Fink, Dwayne H.	Soil Scientist
Freer, Karen K.	Clerk-Typist (resigned September)
French, O. Fred	Agricultural Research Technician
Gerard, Robert J.	Agricultural Research Technician
Gilbert, R. Gene	Soil Scientist
Idso, Sherwood B.	Research Physicist
Jackson, Ray D.	Research Physicist
Kimball, Bruce A.	Soil Scientist
Lance, J. Clarence	Soil Scientist (transferred to NPS, March)
Legard, Wilde W.	Physical Science Technician
Lewis, Clarence	Machinist
Martinez, Juan M. R.	Physical Science Technician
Mastin, Harold L.	Physical Science Technician
Miller, J. Bennett	Physical Science Technician
Mills, Terry A.	Computer Specialist
Mitchell, Stanley T.	Physical Science Technician
Moore, Linda	Physical Science Technician
Murphy, B. Lenore	Clerk-Typist
Nakayama, Francis S.	Research Chemist and Research Leader
Olson, Marian E.	Clerk-Typist (retired May)
Paluska, Michelle M.	Plant Geneticist (resigned July)
Pinter, Paul J., Jr.	Research Entomologist
Pritchard, John M.	Physical Science Technician (retired October)
Rasnick, Barbara A.	Physical Science Technician
Reega, Marilyn T.	Secretary
Reginato, Robert J.	Soil Scientist and Research Leader
Replogle, John A.	Research Hydraulic Engineer and Research Leader
Rice, Robert C.	Agricultural Engineer
Seay, Ronald S.	Agricultural Research Technician
Seiler, Margaret A.	Clerk-Typist (retired January)
Williams, David H.	Physical Science Technician (resigned August)

TITLE: PREDICTING HYDRAULIC CHARACTERISTICS OF CRITICAL-DEPTH FLUMES OF SIMPLE AND COMPLEX CROSS-SECTIONAL SHAPES

NRP: 20740 CRIS WORK UNIT: 5510-20740-003

INTRODUCTION:

The long-throated flumes, particularly the broad-crested weirs, are being widely accepted by the irrigation community worldwide as the preferred device for open-channel flow measurement. Their flexibility in size, liberal construction tolerances, low head-loss requirements, and cross-sectional shape permit them to be retrofitted to most canals. Computer modeling techniques continue to be applied to special problem sites.

GENERAL ACTIVITIES:

A book chapter titled "Flow Measurement Flumes: Applications to Irrigation Water Management" was completed for including as Chapter 6 in the book Advances in Irrigation, edited by Daniel I. Hillel, which should be distributed about June of 1982. In proof copy it consists of 70 book pages of text, tables and figures. The level of the writing was aimed at engineers and scientists not necessarily familiar with flow metering.

A more extensive treatment for audiences not necessarily engineers and scientists, is being completed in a second draft. A rough draft has been completed for all nine chapters, with second drafts for many chapters under way. Only one visit from the cooperating scientist was accomplished during this year. However, review copies are anticipated by June 1982. Other publications dealing with flumes are:

Replogle, J. A., and Clemmens, A. J. 1981. Measuring flumes of simplified construction. Trans. Am. Soc. Agric. Eng. 24(2):362-366.

Replogle, J. A. 1981. Advances in irrigation technology--On farm irrigation practices. Proc. Agric. Sector Symposia--Promoting Increased Food Production in the 1980's. pp. 328-353 (sponsored by the World Bank, Washington, D.C.) Jan. 5-9.

Publications that were distributed during 1981 related to irrigation water management that included major emphasis on measurement of canal flows include:

Replogle, J. A., and Merriam, J. L. 1981. Scheduling and management of irrigation water delivery systems. In Proc. of the Am. Soc. Agric. Eng., 2nd Nat. Irrigation Symp., "Irrigation Challenges of the 80's, Lincoln, NE. pp. 112-126.

Replogle, J. A., Merriam, J. L., Swarner, L. R., Phelan, J. T. 1980. Farm water delivery systems. Am. Soc. Agric. Eng. Monograph "Design and Operation of Farm Irrigation Systems," Chapter 9. pp. 317-343. December 1981.

PARKER ARIZONA STUDY

The cooperative study with the Tribal Council of the Colorado River Indian Tribes (CRIT), the Bureau of Indian Affairs (BIA) and the Soil Conservation Service (SCS) continued into the data collection phases. The flumes that had been installed under our design guidance have been fitted with recording devices. Processing of these records has been delayed by chart-reader failure. Temporarily, facilities at the U. S. Bureau of Reclamation are being borrowed for translating the records to computer-readable data, although the process is more time-consuming than the original system.

A number of problems have been encountered with this study. Many of these problems are typical of field installations, particularly due to the wide variety of flume sites. Also, many of the recorders were in bad repair. The field personnel were somewhat unfamiliar with the maintenance requirements and problems related to the recording devices. The on-farm recorders were installed in 1980, and most were removed in December 1981. These recorders were re-zeroed periodically. The changes in the reading required to re-zero these recorders over approximately a 7-month period is given in Table 1. The standard deviation, s, more accurately effects the magnitude of the errors than the average, $\bar{x}$. Table 2 shows similar results for the off-farm sites.

For the on-farm sites, some data were missed; however, these can be supplemented with district delivery records. Two flumes were not monitored since the irrigator did not cooperate with the study and flooded out the flume. For the off-farm sites, no records are avaiable to supplement lost data. A summary of the data collected is shown in Table 3. For the sites with problems as noted, some of the data can be interpolated or extrapolated manually from fragmentary information. Unfortunately, in some cases, the lost data represents time periods over which water actually flowed. Frequently, we could determine that no flow occurred during a non-recorded period and no record of consequence was lost. However, in many cases, the actual percentage of data lost may actually be more than indicated.

OHIO

In March of 1981, we were contacted by Richard J. Patronsky from the National Technical Center, Soil Conservation Service, Lincoln, Nebraska, concerning consulting assistance for the installation of a large flume for a pilot watershed study on Lost Creek near Defiance, Ohio. The purpose is to monitor watershed runoff quality and quantity during phased-in conservation practices on the watershed. The EPA and SCS were cooperating with a local University and Ohio State University on the project. Most of the funding was from EPA.

This initial contact led to follow-up discussions with SCS Area Engineer, Arthur Brate, at Defiance. We helped him select the design size and furnished the rating tables for a trapezoidal flume for a maximum flow of 800 cfs. Because of the wide required flow range, the throat was triangular, a limiting case for trapezoidal flumes. Table 4 lists the important design dimensions and Table 5 contains an abbreviated calibration.

Ultimately, they requested Agency assistance in supervising the construction of the resulting design. Agency approvals were obtained and a 4-day visit to the site was made in early June 1981. During this time the site was surveyed, prepared, and forms were set for concrete construction. A rainstorm and major flooding damaged the forms before the concrete was placed. Several weeks later, The damaged forms were subsequently repaired and the construction completed with no additional Agency assistance.

Photographs sent to date indicate that channel riprap is needed on a channel curve downstream, but otherwise the flume appears to be adequate both structurally and hydraulically. Freeze-thaw response will need to be monitored since few of these flumes have been installed outside of warm climates.

ARIZONA CANAL

In August 1981, the Salt River Project requested assistance on design recommendations for the Arizona Canal. The peak summer flows are about 2200 cfs. Winter flows are about 200 cfs. A broad-crested weir was chosen that was 4 ft high from the channel bottom, 60-ft wide at the overflow crest, and 12-ft long in the flow direction. The finished newly-lined canal was to be 50 ft wide and have sideslopes of 1.25 horizontal : 1 vertical. A 3:1 ramp was to be placed on the upstream site and a 6:1 exit ramp was added to recover optimum head losses. These are calculated after Bos and Reinick, 1981 (Journal of Irrigation and Drainage, ASCE 107(IR1):87-112), using our model inputs for the calibration factors. We have yet to personally verify the validity of this computation for required head loss, but estimate that the results may be conservative in that it may estimate slightly more head loss required than is found in practice.

Construction difficulties due to hard rock walls and a field surveying adjustment by the construction crew resulted in an as-built weir that was 54 ft wide with 1.214:1 sidewalls, a sill height of 3.94 ft, and a canal bottom of 44.8 ft. Also, the crest elevation, not with respect to the channel bottom, but to absolute datum, was changed downward by 0.7 ft. This would ordinarily have placed the resulting water surface too low for measurement. The calculated head loss was 0.372 ft, and the crest elevation had been chosen to provide about 0.6 ft. However, the reduction in width restores 0.271 ft, which is still about 0.4 low. Unless the new canal bottom and slope provides a flatter water surface profile than anticipated, the flume can be expected to exceed its modular limit at flows above 1400 cfs. If it does exceed its modular limit, a correction procedure will involve adding a 6-inch layer of concrete to the present crest. The weir crest of 12 ft can be shortened to about 10.5 ft to accommodate the 3:1 upstream ramp slope. If the 6:1 downstream ramp is likewise accommodated, another 3 ft of crest is lost. It is recommended that about 9 ft of crest be maintained and that the 1:1 slope be partly maintained for about 3 ft, then tapered into the existing ramp over another 3 ft.

A wall gauge is mounted on the north side of the canal approximately 1 ft from the projected end of the upstream ramp, or about 13 ft from the beginning of the throat. A stilling well is installed at the same location but on the south side of the canal. This will ultimately be fitted with automatic data transmission equipment.

IMPERIAL VALLEY

During the early summer of 1981, the Imperial Irrigation District solicited advice on flow measurements in District laterals. Because these laterals are on relatively steep slopes and sometimes carry discharges up to 90 cfs, a special size was computed which might be designated FCO based on the numbering scheme adapted for Bulletin 2268. The dimensions for these flumes are:

B_1 = 2.00 ft	X_1 = 1.00 ft
B_3 = 4.50 ft	T_L = 3.00 ft
Z_1 = 1.25 ft	C_L = 4.00 ft
Z_3 = 1.25 ft	

Five were installed and fitted with stilling wells, recorders, and wall gauges.

FURROW FLUMES

Dimensions for furrow flumes were standardized in metric dimensions. These flumes are designated according to the bottom width of their throat section. Four sizes have been built and used. A fifth size has not been constructed. The flow measuring range of the flumes are given in Table 6.

The 75-mm size flumes were used by the SCS to evaluate the uniformity of flows in furrow irrigation. They were easily placed and moved. Some difficulty of reading was experienced because of the small point gauges that are necessary. Also, considerably agility is useful in leaning down to observe the point contact with the water. Reading precision is limited to about 1 mm with 0.5 mm possible with extreme care. Thus, field accuracy based on a mid-range reading of 50 mm is ±2% plus the calibration error, which combines to about ±3%. Readings near the lower range limit may approach ±10%.

Several research locations are being supplied with sets of these flumes for evlauation of field use primarily for furrow-flow studies. Locations using them are:

Utah State University	6 flumes, 75 mm
Washington State University	2 flumes, 75 mm
ARS, Fresno, CA	12 flumes, 75 & 100 mm
ARS, Riverside, CA	12 flumes, 250 mm
SCS, Grand Junction, CO	6 flumes, 75 mm
SCS, Arizona	6 flumes, 75 mm

Construction costs appear to be 6-8 man-hours per flume, plus materials, for the smaller versions and 2 to 3 times that for the larger sizes.

Descriptions, dimensions and construction details are in manuscripts in press (Advances in Irrigation, for June 1982). Their major advantages include ease of use, high accuracy and ease of construction (see Annual Reports for 1979, 1980).

SUMMARY AND CONCLUSIONS:

Long-throated flumes, and the related broad-crested weirs which were developed for accurate computer calibration of nearly any size or shape, continue to grow in acceptance by the irrigation community. They are becoming the preferred devices for canal flow measurements because of their ease of construction, accuracy, and low head loss which permits their retrofit to most existing canals as well as to new constructions.

A first draft of a book on measuring flows in irrigation canals is nearly complete. Eight of the nine chapters are ready for first editing. A somewhat condensed version, more oriented to engineering audiences, is being published as a Chapter in Advances In Irrigation, edited by D. I. Hillel, Academic Press; expected publication date, June 1982.

The irrigation district for the Colorado River Indian Tribes, Parker, AZ, continues to install the versions from Bulletin 2278 as their standard measuring device for farm deliveries. The Salt River Project, Phoenix, AZ has installed several special sizes on major laterals for flows of 75 to 150 cfs. Their largest device, put into service in December 1981, is capable of measuring 3000 cfs through its trapezoidal throat of 54-ft bottom width. The calculated head loss is 0.5 ft. This large flume (broad-crested weir) will be the subject of field studies and observations to verify large-scale applications.

The Imperial Irrigation District, Imperial, CA, installed customized versions of the broad-crested weir in several delivery laterals with discharges up to 90 cfs. Operational and water management aspects are being evaluated. Some local farmers in the district are also installing farm-canal sized versions. One farm operator uses plywood copies which he installs temporarily before installing concrete weirs. Only a limited knowledge of hydraulics is thus required for proper selection.

A triangular-throated style with 800 cfs capacity was designed and the construction technically supervised for an Ohio watershed study as a result of a request through the SCS National Technical Center, Lincoln, NE.

Standardized flume sizes have been developed for rectangular and circular canals over a wide range of discharges. The rectangular flumes are being used in the Ebro River Basin, Spain. The circular flumes are being used on the irrigation tail-water monitoring project study at Parker, AZ.

The small furrow flumes which feature low head loss (1 to 3 cm), high accuracy (±2-5%) and insensitivity to device leveling, are being field evaluated by several research cooperators at state universities and several state SCS irrigation evaluation teams.

Foreign inquiries and applications continue to grow (New Zealand, India, Thailand, Sri Lanka, Egypt, Spain).

These flumes and the various modifications to improve ease of construction, observation and field use, are important to provide field-level management information with an ease and accuracy not previously available.

PERSONNEL: J. A. Replogle, A. J. Clemmens

Table 1. Registration errors over time for on-farm recorders, Parker, Arizona. May to December, 1981.

Flume #	Reading Errors Cable jumped (ft)	Zero-shifted (ft)	Remarks
1		-0.084	
2		-0.025	
3		-0.073	
4		-0.057	
5		-.0.25	
6		-0.010	
7		+0.030	
8		-0.100	
9	0.5	-0.02	
10		-0.015	
11		-0.025	
12	---	---	Not studied in 1981
13		+0.008	
14	---	---	Not studied in 1981
15		-0.05	
16		+0.007	
17	0.5	-0.038	
18	0.5	0.000	
19		-0.21	
20	0.5	-0.007	

Notes:

Average zero shift: $\bar{x}$ = -0.039 ft; s = 0.055 ft.
Average zero shift for values (absolute) less than 0.1 ft: $\bar{x}$ = 0.024 ft; s = 0.031 ft
Cable jumped on 4 out of 18 recorders or 22.2%.

Table 2. Registration errors over time for off-farm recorders, Parker, Arizona. May to December, 1981.

Flume #	Reading Errors: Cable jumped (ft)	Reading Errors: Zero-shifted (ft)	Remarks
42		-0.045	
52		0.010	
53		-0.051	
54		-0.140	
55	---	---	Vandalized.
56		-0.010	
57		-0.010	
58	0.5	-0.018	
60	0.5	0.000	
61		-0.26	
62	0.5	-0.010	
63		0.043	
64		-0.115	
66	0.5	-0.040	
67		0.030	
68		0.100	
69		---	Error in original zero setting.
70		0.000	
71		0.000	
72		0.020	
73		---	Not checked-looked close.
74		---	Never re-zeroed
75	0.5	0.000	
76		-0.010	
77	---	---	Damaged
78		0.33	
80	0.5	-0.125	
81		0.03	
82		-0.215	

Notes:

Average zero shift: $\bar{x} = -0.020$ ft; s = 0.111 ft.
Average zero shift for values (absolute) less than 0.1 ft: $\bar{x} = -0.004$ ft; s = 0.026 ft
Cable jumped on 6 out of 27 recorders or 22.2%.

Table 3. Amount of data obtained for off-farm sites, Parker, Arizona. 1981

Flume	Start date	No. Days run	No. Days Good data obtained [a]	Remarks
L42	02-10	324	295	
52	03-04	303	283	
53	02-11	323	281	
54	04-15	260	179	Clock initially had wrong gears.
55	05-08	237	23	Vandalized.
56	03-12	294	219	
57	02-23	311	245	
58			0	Clock not functioning.
60	03-18	288	238	
61	02-11	323	272	
62	02-11	323	244	
63	02-12	322	280	
64	02-11	323	267	
66	02-23	311	267	
67	02-23	311	274	
68			0	Wrong gears on clock.
69	03-25	281	166	Clock initially had wrong gears.
70	07-12	322	291	
71	03-18	288	241	
72			0	Float hanging up--not sure of problem.
73	02-12	322	291	
74	02-12	322	184	Beavers constructed dam on flume.
75	03-25	281	245	
76	03-27	279	252	
77			0	Damaged.
78	04-08	267	13	Bad clock/wrong gears/ submerged.
80			0	Water too turbulent.
81	04-18	267	252	
82	04-25	250	204	

[a] Additional data are retrievable in some instances, but would require selective judgments.

$\bar{x} = 187 \quad n = 28 \quad s = 112$

$\frac{\bar{x}}{365} = 51\%$ of year.

$\frac{\bar{x}}{324} = 58\%$ of record period.

Table 4. Dimensions for Definance, Ohio pilot watershed flume.

Approach channel bottom width, B_1	= 4.0 ft
Converging transition length, T_L	= 6.0 ft.
Throat bottom width, B_3	= 0.0 ft.
Throat length, C_L	= 5.0 ft.
Sideslopes of approach channel, Z_1	= 4.0 ft.
Sideslopes of throat, Z_3	= 4.0 ft.
Exit transition length	= 6.0 ft.
Exit channel length	= 6.0 ft
Gauge location from converging transition, X_1	= 2.0 ft.

Table 5. Abbreviated calibration table for flume as dimensioned in Table 1.

y_1 ft.	Q cfs	y_1 ft.	Q cfs
0.30	0.412	1.75	40.24
0.40	0.870	2.00	57.05
0.50	1.553	2.50	102.3
0.60	2.491	3.00	165.0
0.70	3.714	3.50	212.0
0.80	5.250	4.00	351.0
0.90	7.126	4.50	465.0
1.00	9.368	5.00	631.0
1.25	16.735	5.50	811.0
1.50	26.910		

Table 6. Flow measuring ranges for furrow-type flumes.

Flume designation	Minimum flow			Maximum flow		
	ℓ/s	cfs	GPM	ℓ/s	cfs	GPM
75 mm	0.13	0.0046	2.0	5.0	0.18	80
100 mm	0.29	0.010	4.5	0.5	0.33	150
150 mm	0.75	0.026	11.6	26.0	0.92	410
250 mm	2.3	0.08	36.0	95.0	3.30	1500
400 mm	12.0	0.42	188.0	400.0	14.00	6000

TITLE: MATHEMATICAL MODELING OF BORDER IRRIGATION HYDRAULICS

NRP: 20740 CRIS WORK UNIT: 5510-20740-003

INTRODUCTION:

Current work in irrigation modeling utilizes dimensional analysis techniques to reduce the number of variables involved in displaying and analyzing model results. Katopodes and Strelkoff (1977) presented a dimensional analysis of the Saint Venant equations which are used in several of the current irrigation models. One of the dimensionless parameters in this analysis in the Froude number, the ratio of inertial to gravity forces. The terms containing the Froude number are all acceleration terms in the momentum equation. Based on physical observation in the field and analysis with the various models, it was concluded that these acceleration terms were negligible and could be eliminated from consideration. This is the basis of the zero-inertia border-irrigation model (Strelkoff and Katopodes, 1977). Clemmens (1978) showed that for a wide range of field data that indeed the Froude numbers were small and the above assumption reasonable.

The purpose of this paper is to discuss the potential of irrigation modeling and the associated dimensional analysis to solve problems in border irrigation. I discuss the solutions which have already been presented, the possible solutions which ultimately could be developed, and methods for developing these solutions.

The Saint Venant Equations

The following analysis is based on the Saint Venant equations in differential form under the assumption of zero-inertia. These equations for continuity and momentum are as follows:

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t} + \frac{\partial z}{\partial \tau} = 0 \qquad (1)$$

$$\frac{\partial y}{\partial x} + s_f - S_o = 0 \qquad (2)$$

where q = flow rate per unit width, y = flow depth, x = distance along border, t = time, τ = infiltration opportunity time, z = infiltrated depth, S_o is the bottom slope, and s_f is the friction slope defined as

$$s_f = \frac{q^2(n/C_u)^2}{y^{10/3}} \tag{3}$$

which was derived from the Manning equation for a unit width stream and where n = Manning roughness coefficient and C_u is the units coefficient.

There are several methods for performing a dimensional analysis. The Buckingham Pi theorem could be used, however, the resulting terms may or may not be significant to the problem involved. In this case, it is simpler to develop the dimensional analysis through the use of reference variables. Define; X = reference distance along border, Y = reference flow depth, Z = reference infiltrated depth, T = reference time, Q = reference unit flow rate, and S = reference friction slope. The stared values of each variable represent the actual value divided by the reference value (e.g., $q^* = q/Q$, $z^* = z/Z$, $S_f^* = S_f/S$). Dividing equation (1) by Y/T results in

$$\Psi^* \frac{\partial q^*}{\partial x^*} + \frac{\partial y^*}{\partial t^*} + K^* \frac{\partial z^*}{\partial \tau^*} = 0 \tag{4}$$

where

$$\Psi^* = \frac{QT}{XY} \tag{5}$$

$$K^* = Z/Y \tag{6}$$

Dividing equation (2) by Y/X yields

$$\frac{\partial y^*}{\partial x^*} + P^*(s_f^* - So^*) = 0 \tag{7}$$

where

$$P^* = \frac{SX}{Y} \tag{8}$$

The above equations require that $S = s_f(Q,Y)$ and $Z = z(T)$. This results in $s_f^* = q^{*2}/y^{*10/3}$. The solution to these equations is now dependent upon the boundary and initial conditions and the values chosen for Ψ^*, K^*, S_o^* and P^*.

or the advance of a continuous stream of water on an infinitely long ield, the only additional boundary condition is the inflow rate q_{in} or q_{in}*. Termination or cutoff of the irrigation stream adds an additional variable, t_{co} or t_{co}*. The field length, L or L*, add still one more. The use of the Manning equation (equation 3) adds no additional non-dimensional parameters. However, the use of a power infiltration function ($z = k\tau^a$) adds k and a to the list of dimensional parameters and a to the list of non-dimensional parameters (Strelkoff and Clemmens, 1981).

Strelkoff and Clemmens (1981) have analyzed the non-dimensional variable involved in the problem. This work is summarized as follows. For advance, the dimensional parameters are q_{in}, n/C_u, S_o, k and a. Dimensional analysis (for two basic units, length and time) indicates that the solution is governed by three parameters out of q_{in}*, Ψ*, k*, S_o*, a, P* and F*, where F* is the Froude number. Our analysis assume F* = 0 and a is determined by the infiltration function and cannot be arbitrarily chosen. This leaves only one additional governing solution variable. Values assigned to the other variables only require that the relationships between the reference variables is maintained. The addition of t_{co} and L add two additional variable, however, these are not necessarily t_{co}* and L*.

Results From Direct Computation

For displaying dimensionless advance on sloping borders with L = ∞, t_{co}* = ∞, Katopodes and Strelkoff (1977) chose q_{in}* = 1, V* = 1, K* = 1, and S_o* = 1. The resulting advance curves were displayed in terms of P* and a. This development of the dimensional analysis was based on normal depth relationships. However, setting S_o* = 1 or S = S_o with Q = q_{in} results in Y = y_n where y_n is the so called normal depth. Clemmens (1978) showed that for sloping borders, K* was more appropriate than P*. Based on this work, Strelkoff and Clemmens (1981) displayed dimensionless advance curves in terms of K* and a with q_{in}* = 1, Ψ* = 1, P* = 1, S_o* = 1,

Their analysis was for the integral form of the Saint Venant equations. An additional variable D* was used to relate the drag to the friction slope and P* was defined as unity. Also included was an additional term, s, to account for nonuniform slopes, where s is the ratio of the local bed slope to the bed slope S_o. An additional set of curves was used to display the maximum advance distance and time relative to advance distance and time at cutoff. Shatanawi (1980) extended this work to include the final distribution of infiltrated water, from which different distribution and efficiency parameters could be determined. (He used slighly different terminology where he defined s_f* as P* with reference slope s_f rather than S and his S_o* = P*S_o* in this work. He also defined $\mathcal{S}_f$ as s_f* used here and $\mathcal{S}$ as s used by Strelkoff and Clemmens.) Clemmens and Strelkoff (1979) displayed dimensionless advance and recession curves for level basins with S_o* = 0 and L = ∞ choosing q_{in}* = 1, t_{co}* = 1, Ψ* = 1, and P* = 1. The resulting curves were in terms of K* and a. The elimination of S_o* allows an additional variable to be fixed. Setting t_{co}* = 1, allowed advance after cutoff to be displayed with no additional governing parameters.

To this point in time, our analysis has shown that for computational purposes it is most convenient to set $\Psi^* = 1$, $q_{in}^* = 1$, P^* (or D^*) $= 1$, and $F^* = 0$. The parameters K^*, $\underline{a}$ and L^* are allowed to vary. This leaves S_o^* and t_{co}^*, one of which can be fixed. For level basins $S_o^* = 0$. Fixing $S_o^* = 1$ for sloping borders results in a solution based on normal depth. Thus, we have two distinct solutions, one for zero bed slope and one based on normal depth. In reality, a level border is simply one limit on the slope of a border. Thus it would seem to make more sense to fix $t_{co}^* = 1$ and let S_o^* vary continuously from zero to some practical extreme. Computationally, the difference between the two should only be represented by a change in magnitude. However, this has caused some problems in the stability of the solution. This problem still needs to be resolve.

Solutions for Design and Management

Direct computations with the model require that Ψ^*, P^*, K^*, S_o^*, q_{in}^*, t_{co}^* and L^* all be fixed. The results of the model are the subsurface profile of infiltrated water, the runoff hydrograph, and flow depth hydrographs (derived from water surface profiles). From these results, different measures of performance can be determined. The reference values for converting these dimensionless variables into dimensional variables must be in terms of S_o, q_{in}, t_{co}, L, n/C_u, k, and $\underline{a}$. As an example consider the dimensionless system used by Strelkoff and Clemmens (1981) and Shatanawi (1980) for sloping borders. They let $\Psi^* = 1$, $P^* = 1$, $Q = q_{in}$, and $S = S_o$ with the added result that $Y = y_n$. Thus $QT = XY$ and $Y = SX$ which results in $X = y_n/S_o$, $T = y_n^2/q_{in}S_o$, where $y_n =$

$$(q_{in}n/C_u)^{6/10}/S_o^{3/10}.$$

The parameters that govern the solution are K^*, t_{co}^*, L^* and $\underline{a}$. The variables used to calculate the reference variables are n, S_o, and q_{in} with t_{co}, L, k and $\underline{a}$ used in calculating the governing parameters.

The drawback to displaying the direct results of the computations is that t_{co}^* and thus t_{co} are solution variables, or independent variables and must be known to obtain a solution. For design and management, it would be better if they were dependent variables and not show up directly. Once the model has been run and a number of results obtained, they can be displayed in any form as long as the relationships between the reference, the dimensionless and the dimensional variables are maintained. This will assure that for a given set of actual conditions (dimensional variables) all solutions displayed will yield the same results.

The choices of dimensionless variables have, in a sense, been dictated by computational requirements. Consider some additional variable which may be of interest for analyzing the results of an irrigation. The first is the desired depth of application, z_d. This is the depth of water needed to fill the available root zone storage. If the entire root zone is adequately irrigated, then the application efficiency (volume or average depth required to fill the root zone storage/volume or average depth applied) is

$$E_a = \frac{z_d\ L}{q_{in}\ t_{co}} = \frac{z_d^*\ L^*}{q_{in}^*\ t_{co}^*} V^*\ K^* \qquad (9)$$

If the desired result is E_a, then z_d^* would be added to the list of governing parameters. For any given computational run, there are an infinite number of possible values for z_d and E_a.

Another variable of interest is the minimum or net depth of application, z_n. The performance of the irrigation can then be defined in terms of the distribution uniformity (minimum depth infiltrated divided by the average depth infiltrated)

$$DU = \frac{z_n\ L}{q_{in}\ t_{co}\ (1-RO)} = \frac{z_n^*\ L^*\ V^*\ K^*}{q_{in}^*\ t_{co}^*\ (1-RO)} \qquad (10)$$

where RO = runoff fraction. Another measure of performance is the low quarter distribution uniformity

$$DU_{\ell q} = \frac{z_{\ell q}\ L}{q_{in}\ t_{co}\ (1-RO)} = \frac{z^*_{\ell q}\ L^*\ V^*\ K^*}{q_{in}^*\ t_{co}^*\ (1-RO)} \qquad (11)$$

where $z_{\ell q}$ = average depth infiltrated in the quarter of the field receiving the least amount of water. For any given computational run, there is one and only one value for each of DU and $DU_{\ell q}$. Thus, these are preferred to E_a for describing the results of an irrigation.

The next parameter to be added to the list is the time required to infiltrate the net depth (or the desired or low quarted depth depending on which is being evaluated) of application, τ_n. This can be an important parameter for the design and management of surface systems. The dimensionless parameter τ_n^* can be used to replace K^* as follows: $z_n^* = (\tau_n^*)^a$, $z_n^* = z_n/Z = z_nY/ZY$, $z_n^* = z_n'/K^* = (\tau_n^*)^a$, where $z_n' = z_n/Y$. Thus, $\tau_n^* = (z_n'/K^*)^{1/a}$. (Note, since $z_n' = z_n^*K^*$, Z can be ignored from this analysis and z_n referenced to Y rather than Z. This does not eliminate K^* (or τ_n^*) as a governing parameter.)

Analysis of Dimensionless Schemes

Tables 1 and 2 show the different dimensionless schemes that have been used or could be used. Table 1 shows the level basin systems used by Clemmens and Strelkoff (1979) and later by Clemmens, Strelkoff and Dedrick (1981). The first system, A, was used for direct computations. The next six systems result from the different possible combinations of variables for X, Y, Q, and T. Since the slope is fixed at zero, normal depth has no relevance and cannot be used as a reference variable. (An interesting and useful result of replacing K* with t_n* is that a is eliminated from the calculations of reference and solution variables.) The B and C systems were used for developing design limits and management aids. The last four systems were deemed not useful for level basins. The resulting solutions have three independent variables and one (or more) dependent variables such as DU. These can be displayed by a set of graphs (i.e., for different values of a).

Table 2 shows the possible combinations of reference and solution variables for sloping borders. System D is used for direct computations and was discussed earlier. System O is an alternate method for direct computations. The remaining systems, E to N, result from the possible combinations of reference variables. These results, instead of a single set of graphs with each graph representing one variable, must be displayed by a set of sets of graphs (or a book of chapters of graphs), since there is now an additional variable. Determining which combination of independent solution variables will give the most useful solution requires a considerable amount of judgement. This judgement is based upon the application of these solutions to actual field conditions. It may be useful to think of the solution variables as if they were dimensional. Then the chart would represent the solution for fixed values of the parameters used as reference variables.

For level basins, this analysis was rather straightforward. The B system represents a sensitivity analysis on infiltration. The C system was similar in form to the Soil Conservation Service (SCS) level-basin design charts (1974). The remaining four systems were mixes of these two and not considered very useful for level basins. For sloping borders, the analysis is not as straightforward. In fact, it requires some examination into the equations for the remaining reference variables. The two systems analogous, to the B and C systems are the I and L systems, where the level-basin solutions are an extreme with S_o* = 0.

For sloping borders there are several concepts or relationships which may be useful. The SCS design of sloping borders is based on having water at the upstream end of the field for a time long enough to infiltrate the desired amount which is assumed to be the net amount of water, τ_n. Thus if we let $t_{co} = \tau_n - t_{lag}$, where t_{lag} = time between cutoff and the start of recession, then this criteria is satisfied. Since distribution uniformity is related to the product t_{co} q_{in}, it may be interesting to plot τ_n* versus q_{in}* to study the usefulness of this criteria and the effects of lag time. There are three dimensionless systems in Table 2 which have these as two of the four parameters. The other parameter in addition to a, is one of z_n', L* or S_o* for the E, F and K systems respectively. However, since DU is a function of L, z_n, t_{co}, and q_{in}, it is more useful if these variables are either fixed (used in calculating reference values) or displayed along the axes of the graph and not varied from graph to graph. Thus, the K system with L and z_n fixed is preferred.

Then only the relative slope varies from graph to graph. Also, $S_o^* = S_oL/z_n$, which may be of interest on mildly sloping ponded borders when trying to determine how much slope should be put on the field. For the F system, $L^* = S_oL/z_n$, however, L varies from graph to graph. Other systems are more convenient for observing trends with L. For the E system, $z_n' = z_n/S_oL$. Again for the relationship q_{in} versus τ_n, this dimensionless system is not as useful.

Another relationship, which is used by the SCS, is q_{in} versus L. This is found in the F, H, and L systems with one of τ_n^*, z_n', and S_o^* as the other variable. For looking at this relationship, it might not be particularly useful to let z_n or τ_n change without the other. This leaves only the L system. Similar discussions eliminate the J, M, and N systems from analysis. However, for a particular set of circumstances any one of these might be appropriate.

The last relationship which may be useful is the plot of τ_n versus z_n. This was extremely useful in the analysis of level basins, and was used to determine practical limits on field length (Clemmens and Dedrick 1981). This relationship can result from the E, G, and I systems, with q_{in}^*, L^*, and S_o^* as the third parameter. The I system will probably be useful since it is an extension of the level basin solution where $S_o^* = 0$. The E system may be useful for determining the optimum flow rate and cutoff time for a fixed slope, roughness, and field length, and variable infiltration. The G system does not appear to be useful, however, this results in $L^* = S_oL/y_n$ which looks like it may be useful for some type of analysis (i.e., surge flow analysis).

The systems with the most promise are the I, K, and L systems followed by the E, F, G systems. The former all having S_o^* as parameter and the latter, τ_n^*. The E, F, G, I, and K systems have one positive feature in that the third variable is a very simple function of slope. The system chosen for analysis depends upon the particular use that the user has in mind. The results obtained strongly depend upon the ingenuity of the investigator.

Dimensionless Transformations

As mentioned previously, once the model has been run for the full range of conditions that are likely to exist, the results can be displayed in any form. However, this would require a transformation of the original results in terms of parameters used in the computations to the new form in terms of a new set of parameters. The transformation must be made such that the relationships between the dimensionless variables, the reference variables, and the dimensional variables are maintained for both systems. This insures that for a given set of dimensional input conditions, the results will be identical for any of the dimensionless representations.

For level basins, there are four parameters to be displayed; the three solution variables in Table 1 and the measure of performance (e.g., application efficiency). This can be displayed by a single set of graphs. The axes of the graph are used as two parameters, the curves on each graph represent fixed values of the third parameter and each graph represents a fixed value of the fourth parameter. The infiltration exponent and the measure of performance must remain fixed from one dimensionless system to another, and thus are appropriate for describing the curves of each graph and the graphs. The remaining two parameters become the axes of the graph.

However, direct computation of the model does not result in even (fixed) values of DU. Thus, these must be obtained through interpolation. The error of interpolation involved should be relatively minor since the computations tend to result in relatively smooth curves or relationships, provided that major changes in the time step and other strictly computational variables do not exist. This method was used by Clemmens, Strelkoff and Dedrick (1981). Once the transformed relationships have been developed, additional interpolations could be made to display either of the other solution variables in terms of fixed values if desired.

For sloping borders, there are five parameters to be displayed; the four solution variables and the measure of performance. (For borders with runoff, more than one measure of performance may be required. However, it could be handled by two sets of curves per graph.) These results can be displayed by a set of sets of graphs. (This could be thought of as a book of chapters of pages.) In this case there must be three parameters with fixed values in order to produce meaningful results. The third will require an interpolation, in addition to that for DU, such that a constant value of this parameter will result. This second interpolation depends upon the relationships between the two sets of dimensionless parameters. These relationships for the I, K and L systems are presented in Table 3 based on computation with the D system. The interpolation is relatively straightforward. To develop results for the K systems with constant values of $S_o{}^*{}_K$ (and the axes representing $q_{in}{}^*{}_K$ and $\tau_{nK}{}^*$), start with a solution for L^*_D versus DU for fixed values of $\underline{a}$, K^* and $t_{co}{}^*$. Interpolate for even values of DU. Then plot L^*_D versus $z_n{}'_D$ with $\underline{a}$ and DU fixed for each chart and either K^* or $t_{co}{}^*$ as fixed values on the curves. Lines drawn from the origin represent constant values of $S_o{}^*{}_K$ since $S_o{}^*{}_K = L^*_D/z_n{}'_D$. Thus the intersection of these radial lines with the curves from the analysis represent the points at which the transformation is made. For the I system, horizonal lines would represent constant values of $S_o{}^*{}_I = L^*{}_D{}^{10/13}$ (Table 3).

Once these transformed graphs are produced, the real analysis begins and many currently unknown relationships can be discovered or existing theories quantified.

SUMMARY AND CONCLUSIONS:

A dimensional analysis technique has been developed that can be a powerful tool for displaying the results of irrigation models. The techniques developed allow for considerable flexibility in the choices for the possible combinations of variables for analyzing sloping borders. Thus, it is possible to develop a number of different solutions which could be used to analyze different types of problems. Thus, the potential for applying these results to practical situations is limited only by the ingenuity of the investigator. Three particular combinations of variables were chosen has having the most potential, however, others may be equally as useful.

A new version of the border irrigation model has been developed through contract work. This version will potentially eliminate the problems encountered in previous versions. This model will go through rigorous testing over the next year. It will be used in the analysis of sloping border irrigation systems. Some work has completed on the analysis of runoff-recovery systems through cooperative work with the University of Arizona.

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PERSONNEL: A. J. Clemmens

Table 1: Dimensionless Systems for Level Basins

System	X	Y	Q	T	S	Dimensionless variables in solution	Dependent results	Parameters for reference variable calculations	Comments
A	–	–	q_{in}	t_{co}	–	a, K*, L*	z_n, y^*_{max} 1/	q_{in}, t_{co}, n	Used for level basin computations
B	L	–	q_{in}	–	–	(a) 3/, z_n', τ_n^*	t_{co}^* 2/, y^*_{max}	q_{in}, L, n	Used for analyzing level basin design
C	–	z_n	–	τ_n	–	(a), q_{in}^*, L*	t_{co}^*, y^*_{max}	τ_n, z_n, n	Used for analyzing level basin design
–	L	z_n	–	–	–	(a), q_{in}^*, τ_n^*	t_{co}^*, y^*_{max}	L, z_n, n	Nor used (may be of interest, to extend sloping solution)
–	L	–	–	τ_n	–	(a), q_{in}^*, z_n^*	t_{co}^*, y^*_{max}	L, τ_n, n	Not used
–	–	z_n	q_{in}	–	–	(a), L*, τ_n^*	t_{co}^*, y^*_{max}	z_n, q_{in}, n	Not used
–	–	–	q_{in}	τ_n	–	(a), L*, z_n^*	t_{co}^*, y^*_{max}	q_{in}, τ_n, n	Not used

1/ y^*_{max} is the maximum flow (surface water) depth

2/ t_{co}^* is replaced with DU from Eq. 10 for displaying results (note RO = 0).

3/ ( ) indicates that the parameter a is not required for the calculation of the reference variables.

Table 2: Dimensionless Systems for Sloping Borders

System	Reference Variables X	Y	Q	T	S	Dimensionless variable in solution	Dependent results	Parameters for reference variable calculations	Comments
D	–	(y_n) 1/	q_{in}	–	S_o	$\underline{a}$, K*, t_{co}*, L*	z_n', RO, y^*_{max}	n, S_o, q_{in}	Used in sloping border advance commputations
E	L	–	–	–	S_o	($\underline{a}$), q_{in}*, z_n', τ_n*	t_{co}*, RO, y^*_{max}	n, S_o, L	May be useful
F	–	z_n	–	–	S_o	($\underline{a}$), L*, q_{in}*, τ_n*	t_{co}*, RO, y^*_{max}	n, S_o, z_n	May be useful
G	–	(y_n)	q_{in}	–	S_o	($\underline{a}$), L*, z_n', τ_n*	t_{co}*, RO, y^*_{max}	n, S_o, q_{in}	May be useful
H	–	–	–	τ_n	S_o	($\underline{a}$), L*, q_{in}*, z_n'	t_{co}*, RO, y^*_{max}	n, S_o, τ_n	Not useful
I	L	–	q_{in}	–	–	($\underline{a}$), S_o*, z_n', τ_n*	t_{co}*, RO, y^*_{max}	n, L, q_{in}	Similar to B system with S_o* added (limited use)
J	L	–	–	τ_n	–	($\underline{a}$), S_o*, z_n', q_{in}*	t_{co}*, RO, y^*_{max}	n, L, τ_n	Not useful
K	L	z_n	–	–	–	($\underline{a}$), S_o*, τ_n*, q_{in}*	t_{co}*, RO, y^*_{max}	n, L, z_n	Potentially useful
L	–	z_n	–	τ_n	–	($\underline{a}$), S_o*, L*, q_{in}*	t_{co}*, RO, y^*_{max}	n, z_n, τ_n	Similar to C system with S_o* added – useful
M	–	z_n	q_{in}	–	–	($\underline{a}$), S_o*, L*, τ_n*	t_{co}*, RO, y^*_{max}	n, q_{in}, z_n	Not useful
N	–	–	q_{in}	τ_n	–	($\underline{a}$), S_o*, L*, z_n*	t_{co}*, RO, y^*_{max}	n, q_{in}, τ_n	Not useful
O	–	–	q_{in}	t_{co}	–	$\underline{a}$, K*, S_o*, L*	z_n, RO, y^*_{max}	n, t_{co}, q_{in}	Could be used for computations

1/ Since by definition $S = s_f(Q, Y)$ fixing $Q = q_{in}$, $S = S_o$, results in $Y = y_n$, since $S_o = s_f(q_{in}, y_n)$.

3: Transformation relationships for displaying model results based on computation with the D system.

n	X	Y	Q	T	S	L^* (L/X)	z_n' (z_n/Y)	q_{in}^* (q_{in}/Q)	τ_n^* (τ_n/T)	S_o^* (S_o/S)
	L	$L^{3/13} q_{in}^{6/13} \left(\frac{n}{C_u}\right)^{6/13}$	q_{in}	$\frac{L^{16/13}\left(\frac{n}{C_u}\right)^{6/13}}{q_{in}^{7/13}}$	$\frac{q_{in}^{6/13}\left(\frac{n}{C_u}\right)^{6/13}}{L^{10/13}}$	1.0	$\frac{z'_{n_D}}{L^{*3/13}_D}$	1.0	$\frac{\tau^*_{n_D}}{L^{*16/13}_D}$	$L^{*10/13}_D$
	L	z_n	$\frac{z_n^{13/16}}{\frac{n}{C_u} L^{1/2}}$	$\frac{L^{3/2}\frac{n}{C_u}}{z_n^{7/6}}$	$\frac{z_n}{L}$	1.0	1.0	$\frac{1}{z'^{13/6}_{n_D}}$	$\frac{\tau^*_{n_D} z'^{7/6}_{n_D}}{L^{*3/2}_D}$	$\frac{L^*_D}{z'_{n_D}}$
	$\frac{z_n^{7/9}\tau_n^{2/3}}{\left(\frac{n}{C_u}\right)^{2/3}}$	z_n	$\frac{z_n^{16/9}}{\tau_n^{1/3}\left(\frac{n}{C_u}\right)^{2/3}}$	τ_n	$\frac{z_n^{2/9}\left(\frac{n}{C_u}\right)^{2/3}}{\tau_n^{2/3}}$	$\frac{L^*_D}{z'^{7/9}_{n_D}\tau^{*6/9}_{n_D}}$	1.0	$\frac{\tau^{*3/9}_{n_D}}{z'^{16/9}_{n_D}}$	1.0	$\frac{\tau^{*6/9}_{n_D}}{z'^{2/9}_{n_D}}$

TITLE: IRRIGATION WATER MANAGEMENT FOR RICE PRODUCTION IN THE SOUTHWESTERN UNITED STATES

NRP: 20740 CRIS WORK UNIT: 5510-20740-003

INTRODUCTION:

Rice research began in 1979 at El Centro, California, and Yuma, Arizona. The objectives of these experiments have been: (1) to determine rice cultivars suitable for an arid environment; (2) to evaluate the effects of irrigation regime and planting date on non-paddy rice production; and (3) to determine water requirements and estimate consumptive use for the southwestern United States, utilizing level-basin irrigation systems. This annual report includes information obtained from El Centro for 1980 and Yuma for 1981.

El Centro, California

Field Procedures:

Three investigation were conducted at the Imperial Valley Field Station, El Centro, California, with the primary purpose being to identify rice cultivars that would be suitable for desert irrigation practices. The first experiment was called 1980 intermittent irrigation experiment-advanced cultivars. Fifty entries were planted on April 19 and May 16 and 25 entries on June 19, using three irrigation schedules of paddy, 3-, and 6-days between water applications. Each entry was planted in rows 2.4 m (8 feet) long on 30 cm (12 inch) centers and replicated four times. A seeding rate of 8 grams per row was used, and Ordram (molinate, S-Ethyl hexahydro-1, H-azepine-1-carbothioate) was applied at about 34 kg/hectare (30 pounds/acre) as a preplant herbicide. Nitrogen fertilizer was applied at 68 kg/hectare (60 pounds/acre) preplant, 68 kg/hectare (60 pounds/acre) during tillering, and 1 kg/hectare (90 pounds/acre) at boot (or panicle initiation).

Of the 50 entries that were used in this first experiment, there were actually 36 different cultivars. For some of the more advanced lines, seeds originating from the 1979 paddy, 3-, 6-, and 9-day irrigation treatments were planted under the three irrigation schedules to see if they could be improved or may have changed through natural selection. The cultivars handled in this manner were IR 22, IV 213, IV 330-1, IV 404, TI, IR 1108-3-5-3-2. Data taken included general appearance, save and discard, heading date, plant height, panicle exsertion, grain type, percent lodging, percent sterile panicles, percent blanking, weight per 200 seeds, stem angle, and yield.

The second experiment was named 1980 intermittent irrigation experiment-cultivar selections. Here, 50 promising selections taken from previous experiments and nurseries were planted on April 19, May 16, and June 13 and irrigation under paddy, 3-, and 6-day treatments. Plot size, replication number, seeding rate, and herbicide and fertilizer procedures were the same as the first experiment. Abbreviated data obtained from this second experiment were general appearance, save and discard, heading date, plant height, and percent sterile panicles since the main objective was to identify and increase the seed supply of the promising selections.

Seventy new lines and check cultivars were planted in a third experiment, named 1980 intermittent irrigation experiment-new cultivars. These new lines were selected from the introduction nursery grown in 1979. Since the availability of seed was limited, these lines were planted on only one date May 15, with one replication. However, the three irrigation treatments of paddy, 3-, 6-day intervals were utilized. Plot size and other agronomic practices were the same as the two previously described experiments. Limited notes including general appearances, save and discard, heading date, and plant height were taken on this material. The general appearances and save-discard notes were used to determine which lines would be harvested and grown in 1981. Seed increase plots of 18 cultivars and an introduction nursery of 1174 entries were also planted in 1980 from which good appearing lines were selected for future plantings.

In the 1981 plantings which are still being analyzed, the five main components were: (1) advanced cultivars, (2) cultivar selections, (3) new lines, (4) seed increase, and (5) introduction nursery. The first three experiments contained 50, 35, and 36 entries, respectively, and were irrigated at the same three levels used in 1980. Notes on about 12 characteristics were obtained on first three experiments, whereas less information was obtained on the last two experiments. Seed increases (component 4) were made for 35 cultivars, and the introduction nursery (component 5) had 1168 lines in 1981.

Results and Discussion:

The analysis of the advanced cultivars and cultivar selection experiments i 1980 showed that the general appearances which provides a visual assessment of an entry, and the save-discard noted gave an excellent overall evaluation of a particular entry. In general, entries with a general appearance value in the 6-day treatment above 5.5 and a save-discard value in the same treat ment above 1.5 would probably be discontinued, except for the check cultivars. Percent blanking and yield were closely related to the general appearance and save-discard notes. Both can be highly variable within and between seasons since they can be strongly influenced by varying temperatures during the growing season. Often, information from two or three years is needed to separate the average from the best lines. Percent sterile panicles (white) give a quick, easy note on the poorest cultivars.

Tables 1-3 presents the results from the 1980 intermittent irrigation experiment-advanced cultivars for the three irrigation treatments and three planting dates. The performance of most of the advanced cultivars seemed to be better in the second planting date (May 16, Table 2) than the other two planting dates (April 19, Table 1; June 19, Table 3). Production appeared to be adversely affected by soil salinity in the first planting date (April 19), which caused some of the lower yields from lines such as Al Nam Tsar 1. IR 22 from LE 6, IV 330-1, and IV 404. Soil salinity generally resulted in poorer stands and seemed to increase yield variability, which could be the reason why lines like IV 404-6 (entry 16) in the first planting date had higher yields with less frequent irrigations compared with the flood treatment.

Soil salinity samples were taken before and after the irrigation experiments, and the results are given in Table 4. Leaching of salts was generally improved with the intermittent irrigation treatments (3-and 6-day intervals between irrigations) over the paddy treatment. More leaching occurred at the 30-cm (1 foot) soil depth than at 60-cm (2 foot) depth. Little difference in the leaching of salts was observed for the three different planting dates.

For the cultivars IR 22, IV 213, IV 404, T1, and IR 1108-3-5-3-2 that were planted from different seed sources in the advanced cultivar experiment, weaker plants and lower yields seemed to result from the weaker, smaller seeds produced under the 3-and 6-day irrigations compared with the continuous flood. No other real differences were noted at this time, and additional generations will need to be carried out to see if any long-term effects can be exhibited.

Overall, some of the more promising lines in the advanced cultivar experiment were IV 404, IV 213, IR 22, IR 1108-3-5-3-2, PI 324 426, PI 433 220, and PI 432 560. They had similiar yields and other characteristics for the flood, 3-, and some 6-day irrigation schedules. On the other hand, yields decreased sharply with the drier irrigation treatments compared with the continuous flood for cultivars such as M 101, Nato, PI 391 232, and others. Plant growth characteristics changed in the following manner as the number of irrigations were reduced except on a few of the more promising varieties: heading dates lengthened, height shortened, blanking increased, percent sterile panicles increased, and yield decreased. Changes in the other growth characteristics were smaller, but they seemed to react as follows: panicle exsertion was reduced, grain type was shorter, lodging was less, and weight per 200 seeds was reduced. Thirty-one entries were saved from the 1980 advanced cultivar experiment for planting in 1981. Replanting and retesting are required because some cultivars appear to escape the full effects of high temperatures by passing through critical growth stages when the climate has moderated for a few days.

On the second experiment-cultivar selections, all lines except those that were high-producing in other experiments (IR 22, IR 442-2-5-8, T1, IV 213, IV 404, etc.) had a poor performance when judged on a row basis (data not shown). Work conducted in 1979 suggested that some plants in the 3- and 6-day irrigation treatments might be better than their parents. When critically observed in 1980, selections of individual plants made from previous years (IV 62-1-0, IV 62-2-0, IV 213-6, IV 213-7, IV 404-5, IV 404-7, etc.) responded similarly or with little change from prior years. The second planting date (May 16) was the best, but the date of planting did not appear to increase the ability to select improved plants within a row.

For the third experiment-new cultivars, seed was harvested from 18 out of 70 new lines and selections (data not shown). Fourteen of these were then planted in the 1981 intermittent irrigation experiment-advanced cultivars.

Yuma, Arizona

Field Procedures:

Six rice cultivars (IV 404, IV 213, IR 22, IR 1108-3-5-3-2, Taichung 181, and IV 330-1) were planted on four dates (March 4, April 1, April 29, and May 27) in the 1981 intermittent irrigation experiment. For each planting date, the three irrigation treatments included applying irrigation water either twice a week, once a week, or every 10 days. Each variety was replicated four times within each irrigation treatment. The drilling rate was .2 kg/hectare (100 lbs/acre), and the rows were spaced 18 cm (7 inches) apart. In addition, an observational nursery of 32 cultivars was planted on all four planting dates.

A preplant application of Ordram herbicide (molinate, S-Ethyl hexahydro-1 H-azepine-carbothioate) at a rate of 22 to 34 kg/hectare (20 to 30 lbs/acre) was applied for general weed control. A post-emergence application of Stam M4 (propanil, 3',4'-Dichlorophenylpropionanilide) at a rate of 7 liters/hec-tare (3 qts/acre) was also applied for control of grasses, at the 2-3-leaf stage on April 20, May 19, May 28, and June 18 for the four planting dates, respectively. Nitrogen fertilizer in the form of urea was broadcast and incorporated before planting at 56 kg/hectare (50 lbs/acre) of N, followed by another 56 kg/hectare after tillering and before initial heading on June 25, June 25, August 6, and September 4 for the four planting dates, respectively.

Irrigation water applications were measured with a 10-cm (4 inch) propeller-type water meter, and detailed rice phenology was recorded on all plots. Chemical leaf analyses for nitrogen, phosphorous, potassium, and minor elements were made on the rice leaves at three time during the growing season. The rice was harvested when an entire planting date reached maturity, and yields were based on a 2.7 m^2 (29.2 sq. feet) sampling area for the intermittent irrigation experiment and on a 1.3 m^2 (14.0 sq. feet) area for the observational nursery. Seed weight and nutrient analyses were determined from the harvested grain plus milling and cooking quality tests will be conducted by B. D. Webb, USDA-ARS Rice Research, Beaumont, Texas.

Results and Discussion:

Because of cool night temperatures, the number of days from planting to emergence was 26, 19, 14, and 6 days for the four planting dates on the 19 1 intermittent irrigation experiment. The time period from planting to heading (50% panicles) averaged 172, 147, 133, 99 days for the same four planting dates (March 4, April 1, April 29, and May 27). It was shown that number of days to heading decreased with the later planting dates. Also, heading is delayed as the interval between intermittent irrigation increased from twice a week to every 10 days (Tables 6-9). Table 5 summarizes the water pp cations (irrigation water plus precipitation) which averaged 363, 229, and 195 cm for the three irrigation treatments (two/week, weekly, and every 10 days). Considerably more irrigation water was applied on the twice a week irrigation schedule for the earliest planting date. The ratio of the seasonal water applied to Class A pan evaporation was about 1.50, 1.25, and 1.00 for the three irrigation levels, respectively. From the standpoint of germination time, heading dates, and water application amounts, planting dates of early April through early May (April 1 and April 29) appeared to be best under the conditions of this experiment.

Figures 1 to 4 show the changes in plant height versus time for the various cultivar irrigation treatments, and planting dates. Generally, plant heights were not different for the three irrigation levels until late June, early July, late July, or early August for the four different planting dates, respectively. However, after maximum tillering, the plots that were irrigated twice weekly grew considerably taller than the drier irrigation treatments. Average heading dates, final plant heights, panicle exsertion, percent lodging, stem angle, and yield for the six cultivars and three irrigation treatments are present in Tables 4 to 9 for the four planting dates, respectively. For the four highest yielding cultivars (IV 404, IV 213, IR 22, IR 1108-3-5-3-2), the heading dates are nearly the same; panicles tend to be moderately well exserted, and stem angles are between 20 to 30 degrees from perpendicular, which are the characteristics of a rice cultivar with favorable drought resistance. With these cultivars, yields declined sharply when irrigations decreased from twice to once weekly. Although the highest yields were obtained from the March 4 planting date, the later planting dates of April 1 and April 29 resulted in only slight yield reductions with a significantly shorter growing season and quantity of irrigation water applied. The lower yields for the April 1 planting compared with April 29 was a result of poorer stands. Overall, IV 404, IV 213, IR 22, and IR 1108-3-5-3-2 were the four most promising cutlivars having a potential yield of about 5000 kg/hectare (4500 lbs/acre) when planted near May 1. The IV 404, IR 22, and IR 1108-3-5-3-2 approaches a long grain type, whereas IV 213 is a medium grain rice.

Plant analysis of mature leaves for all six cultivars at three growth stages for the four planting dates is shown in Table 10. Based on plant tissue levels suggested for California rice production (Miller et al. 1973) no distinct differences in nitrogen, phosphate-phosphorous, potassium, or zinc were observed in 1981. Typically, the nitrogen, phosphorous, and potassium values decreased with sampling dates, and the nitrogen percentages in the leaves were slightly lower for the later planting date compared with the three earliest dates. Little differences in the nutrient levels of the harvested grain (Table 10) in terms of nitrogen, potassium, phosphorous, iron, manganese, zinc,or copper was observed between cultivars, irrigation schedules, or planting dates. However, the nitrogen level in the grain is much lower in 1981 than previous year, which translates into lower protein contents and could indicate an improvement in rice quality.

Milling and cooking quality tests were conducted on the 1980 harvested rice, but the results have not been completed on the 1981 grain. Last year's samples (data not presented) showed that grain weight and percent whole kernel rice were less than normal (high quality rice produced under nonstressed conditions). Percent protein chalkiness, and alkali spreading values (one measure of cooking) were greater than the acceptable range of high quality rice.

Yields from the observational nursery planted on the same four dates are found in Table 11. Most cultivars had the highest yields for the April 29 planting date, and production was higher in the nursery than the main irrigation plots. Some of the more promising new cultivars were IR 2268-24-2-3 1, PI 432 560, T1, PI 403 RP 7923, and IR 944-93-2-1-2 with yields similar IV 404, IV 213, IR 22, and IR 1108-3-5-3-2. Sixteen cultivars in the 1981 nursery were selected for planting in the 1982 observational nursery.

The 1982 intermittent irrigation experiment, will consist of six cultivars, two planting dates, six irrigation treatments, and two water qualities. Th water qualities are Colorado River water with 850 mg/l of total dissolved solids used in previous years and groundwater pumped from a water table depth of about 1.5 m below the plots with about 1700 mg/l of dissolved solids. Irrigation includes water qualities and more frequent applications during specific stages of growth. Hybrid rice cultivars have also been added at both the Yuma and El Centro locations.

SUMMARY AND CONCLUSIONS:

Three intermittent rice irrigation experiments were conducted at the Imperial Valley Experiment Station, El Centro, California, in 1980; and two rice irrigation studies were conducted at the Yuma Valley Experiment Station, Yuma, Arizona, in 1981. At El Centro, decreasing the number of water applications typically resulted in later heading dates, later maturit dates, smaller grain size, less lodging, and shorter stature. However, some of the more promising cultivars were IV 404, IV 213, IR 22, IR 1108-3-5-3-2 PI 324 426, PI 433 220, and PI 432 560 where yields were not significantly different for the paddy, 3-day, and some 6-day intervals between irrigations. Cultivar performance was better with the May 16 than the April 19 and June 19 planting dates. In 1982, cultivar selection will be based on varying irrigation in respect to stages of rice growth to determine if yields can be further improved and irrigation water conserved.

At Yuma, 1981 results indicated that IV 404, IV 213, IR 22 and IR 1108-3-5- -2 had a potential to produce around 5000 kg of grain/hectare when planted from April to early May and irrigated at least biweekly. The IV 404, IR 22, IR 1108-3-5-3-2 are mostly of a long grain type, whereas IV 213 is a medium grain rice. Nutrient levels in mature plant leaves and unpolished grain suggested that two nitrogen applications totalling 112 kg/hectare (100 lbs/acre) supplied adequate nutrients under intermittent irrigations. Futu e studies will concentrate on using irrigation water of marginal quality and n increasing the number of irrigations during critical plant growth stages along with decreasing irrigations during other growth periods. The most immediat application of these results would be to demonstrate to countries with food shortages, problem soils in need of reclamation, limited water supplies, and marginal climatic conditions, that research and development on rice production and more careful water management should be considered.

LITERATURE CITED:

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PERSONNEL: D. A. Bucks and O. F. French (U. S. Water Conservation Laboratory); W. F. Lehman and L. K. Gibbs (University of California, Imperial Valley Field Station); R. L. Roth, B. Franco, and E. A. Lakatos (University of Arizona, Yuma Valley Experiment Station).

Table 1. Intermittent rice irrigation experiment-advanced cultivars, planted on April 18, 1980 (Julian Date 108) at El Centro, California.

Cultivar & Entry No.	Source[1/]	Irrigation Treatment[2/]	General Appearance[3/]	Save & discard[4/]	Julian Heading Date	Ht. in cm.	Panicle Exsertion[5/]	Grain Type[6/]	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle[7/]	Yield in gm.[8/]
Al Nam	LE6	F	5.3	1.5	220	55	4.0	2.0	1.3	0	19	4.9	68	54
Tsar-1		3	6.0	1.8	214	46	3.8	1.8	1.5	0	24	4.5	61	61
(1)		6	6.3	2.0	220	39	4.0	2.0	0	0	43	4.0	60	71
IR 22	LEF	F	3.8	1.0	250	71	3.8	2.8	1.5	0	17	4.1	74	351
(2)		3	4.8	1.3	251	64	3.8	2.3	.3	0	22	3.9	69	226
		6	4.5	1.3	258	57	3.8	2.8	.3	0	28	3.4	73	155
IR 22	LE3	F	4.5	1.0	246	73	2.3	3.0	.7	0	27	4.3	70	312
(3)		3	4.3	1.0	251	62	4.0	2.5	2.5	0	26	3.8	70	237
		6	4.5	1.3	259	55	3.8	2.5	0	0	32	4.2	70	121
IR 22	LE6	F	5.3	1.3	246	69	3.7	3.0	1.3	0	13	4.3	75	69
(4)		3	4.3	1.3	251	62	3.8	2.8	1.8	0	27	3.7	70	62
		6	4.7	1.0	257	52	3.7	2.7	.3	0	31	3.9	70	52
IR 26	LE3	F	5.0	1.3	245	66	4.0	2.3	1.0	0	12	4.7	68	--
(5)		3	4.5	1.3	253	59	4.0	1.8	1.5	0	31	3.6	71	178
		6	3.8	1.0	255	50	3.3	2.3	.8	0	28	3.5	70	213
IV 213	LEF	F	4.3	1.3	225	62	3.8	2.5	1.0	0	31	4.7	79	251
(6)		3	3.5	1.0	225	63	3.8	2.0	3.0	0	25	5.5	80	262
		6	5.3	1.5	234	54	3.3	1.8	.8	0	39	3.7	83	234
IV 213	LE3	F	5.3	1.5	224	61	4.0	2.3	.5	0	37	4.5	79	287
(7)		3	4.5	1.3	226	61	4.0	1.8	1.5	0	24	4.8	81	239
		6	5.3	1.3	235	55	3.5	1.8	0	0	37	4.2	80	196
IV 213	LE6	F	5.5	1.5	224	63	4.0	2.0	.8	0	36	4.4	80	241
(8)		3	5.8	1.3	228	61	4.0	2.0	1.8	0	21	4.4	83	299
		6	5.8	1.5	237	54	3.5	2.0	.8	0	31	3.7	84	184

Cultivar & Entry No.	Source[1]	Irrigation Treatment[2]	General Appear-ance[3]	Save & dis-card[4]	Julian Heading Date	Ht. in cm.	Panicle Exsertion[5]	Grain Type[6]	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle[7]	Yield in gm.[8]
IV 213	PR	F	5.8	1.8	222	63	3.8	2.0	.8	0	22	3.8	79	270
(9)		3	6.5	1.8	221	61	3.5	2.0	.5	1.3	31	4.4	80	260
		6	4.3	1.0	232	59	3.3	2.0	.8	0	23	3.8	81	200
IV 213-8	LE3	F	4.3	1.0	223	62	4.0	2.0	.8	0	30	4.3	78	299
(10)		3	4.5	1.0	229	62	4.0	1.8	.8	0	23	4.3	81	277
		6	5.0	1.3	231	54	3.8	2.0	.5	0	38	4.2	79	210
IV 330-1	LE3	F	4.8	1.0	228	64	3.5	2.8	.5	0	27	5.0	70	64
(11)		3	4.3	1.0	241	63	3.8	2.3	.5	0	22	4.6	69	63
		6	4.8	1.3	244	51	4.0	2.5	.5	0	32	4.4	66	57
IV 330-1	LE9	F	6.0	1.8	234	63	4.0	2.8	1.8	0	15	4.4	70	63
(12)		3	5.5	1.5	239	53	3.8	2.5	2.5	0	29	4.9	65	53
		6	5.8	1.8	245	51	3.8	2.8	0	0	29	4.1	65	51
IV 404	LEF	F	4.3	1.0	238	71	3.3	2.3	2.3	0	9	4.3	78	71
(13)		3	3.8	1.0	243	60	3.0	2.3	2.0	0	16	4.1	68	60
		6	3.8	1.0	252	54	3.3	3.0	2.3	0	12	4.1	66	54
IV 404	LE3	F	4.8	1.3	237	63	3.5	2.8	5.0	0	8	4.8	71	63
(14)		3	3.3	1.0	246	55	3.5	2.5	.8	0	11	4.2	70	55
		6	3.5	1.0	253	57	3.8	3.0	2.3	0	12	4.1	69	57
IV 404	LE6	F	5.3	1.3	240	62	4.0	2.5	2.5	0	22	5.2	70	62
(15)		3	3.8	1.0	249	56	3.8	2.5	.5	0	15	4.1	65	56
		6	4.3	1.0	248	54	3.5	2.8	2.5	.3	14	4.3	68	54
IV 404-6	LE3	F	4.8	1.3	239	64	3.5	3.0	4.0	0	12	4.1	74	93
(16)		3	3.3	1.0	245	59	3.5	2.5	1.5	0	20	4.7	65	170
		6	3.8	1.0	253	55	3.5	3.0	.5	0	12	4.6	64	273

Table 1. (Continued).

Cultivar & Entry No.	Source1/	Irrigation Treatment2/	General Appear-ance3/	Save & dis-card4/	Julian Heading Date	Ht. in cm.	Panicle Exertion5/	Grain Type6/	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle7/	Yield in gm.8/
Calrose 76	PR	F	4.8	1.8	224	72		2.0	1.0	0	43	3.0	83	206
(17)		3	4.8	1.3	219	74	2.3	2.0	3.0	0	48	4.7	81	145
		6	7.0	2.0	218	58	1.3	2.0	1.0	0	76	3.3	83	51
Chen Chunya	LE6	F	4.5	1.0	230	60		2.0	.8	0	15	4.2	68	262
(18)		3	4.3	1.0	233	62	4.0	1.3	3.0	0	24	3.8	60	156
		6	5.8	1.8	241	41	4.0	1.5	0	0	38	3.5	61	—
DD 95	LE3	F	6.5	2.0	248	100	3.0	2.3	7.0	0	29	3.4	74	—
(19)		3	6.5	2.0	247	93	3.0	2.0	10.0	25.0	41	3.3	76	—
		6	7.3	2.0	258	85	3.0	1.8	4.8	0	41	3.3	76	121
M 7	PR	F	4.8	1.0	232	75	1.5	2.0	1.3	0	42	4.9	81	251
(20)		3	5.0	1.5	230	76	1.8	2.0	2.5	0	21	4.9	81	169
		6	5.0	1.5	236	66	1.5	2.0	1.0	0	53	5.0	81	68
M 101	PR	F	5.3	1.5	212	63		1.8	.3	0	37	5.2	81	170
(21)		3	7.5	2.0	208	59	2.5	2.0	.5	0	42	4.3	83	63
		6	8.0	2.0	211	41	2.5	2.0	0	1.3	85	0	84	13
Nato	LEF	F	6.8	2.0	230	86		2.3	1.0	50.0	75	4.9	79	105
(22)		3	7.5	2.0	233	77	2.0	2.3	0	21.3	93	3.3	81	26
		6	8.0	2.0	239	66	2.0	2.0	0	37.5	91	4.0	84	13
Pokkeli		F	6.8	2.0	271	113	3.0	2.8	.8	12.5	78	4.5	75	6
(23)		3	8.3	2.0	275	106	3.5	2.0	.3	16.5	79	0	78	4
		6	8.3	2.0	287	94	4.0	2.5	0	42.5	100	0	74	—
Shioji 74	PR	F	5.8	1.8	233	67	3.5	3.0	.5	0	10	4.7	73	165
(24)		3	4.8	1.3	247	57	3.8	2.3	2.0	12.5	24	4.5	66	195
		6	5.8	1.5	249	61	3.8	2.3	.5	0	19	3.8	65	—

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Cultivar & Entry No.	Source[1]	Irrigation Treatment[2]	General Appear-ance[3]	Save & dis-card[4]	Julian Heading Date	Ht. in cm.	Panicle Exsertion[5]	Grain Type[6]	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle[7]	Yield in gm.[8]
T1	LEF	F	4.8	1.0	238	64	3.8	2.0	.3	0	13	4.5	73	261
(25)		3	5.0	1.3	248	58	4.0	2.0	.8	0	13	3.8	69	263
		6	4.8	1.3	263	50	3.8	2.8	.8	0	17	3.5	75	167
IT1	LE3	F	4.5	1.0	241	60	3.8	2.5	.3	0	18	4.0	69	359
(26)		3	4.0	1.0	243	58	3.8	2.0	.8	0	16	3.5	69	348
		6	4.0	1.0	254	55	3.0	2.5	.3	0	31	3.5	78	236
IT1	LE6	F	5.3	1.3	243	63	3.8	2.0	2.3	0	21	4.2	71	270
(27)		3	4.5	1.0	245	55	4.0	2.0	1.5	0		Mixture	71	150
		6	4.5	1.0	250	58	3.3	1.8	.3	0	19	3.9	68	255
T1	LE9	F	5.0	1.3	258	71	3.0	3.0	0	0	11	4.6	77	--
(28)		3	5.3	1.3	256	59	3.5	2.5	.5	0	8	4.0	79	75
		6	6.3	2.0	264	57	3.7	3.0	0	0	38	3.6	80	--
T181	LE6	F	5.0	1.3	243	77	1.5	1.3	1.8	0	22	5.5	81	335
(29)		3	4.5	1.3	249	79	1.8	1.0	1.3	8.8	39	4.6	84	194
		6	6.3	1.5	256	73	2.3	1.0	1.0	0	19	4.5	80	121
IR 422-2-58		F	5.0	1.3	254	82	4.0	3.0	1.5	0	4	3.9	69	369
(30)	LE3	3	5.0	1.5	259	72	4.0	2.8	.5	6.3	16	3.8	73	281
		6	5.0	1.3	269	69	4.0	3.0	2.0	2.5	35	3.7	71	181
IR 944-93-2-1-2-2		F	5.3	1.3	246	66	3.7	3.0	0	0	10	4.4	73	--
(31)	LE3	3	4.3	1.3	249	62	3.0	2.5	1.8	0	24	3.9	64	--
		6	4.8	1.0	255	61	3.3	3.0	1.3	0	22	3.7	70	84
IR 1108-3-5-3-2		F	4.0	1.0	239	71	3.3	3.0	1.3	0	26	4.4	76	419
(32)	LEF	3	4.5	1.3	245	66	3.8	2.3	.3	0	16	4.1	78	240
		6	4.5	1.3	244	55	3.3	3.0	.5	0	33	3.8	79	--

Table 1. (Continued).

Cultivar & Entry No.	Source[1/]	Irrigation Treatment[2/]	General Appearance[3/]	Save & discard[4/]	Julian Heading Date	Ht. in cm.	Panicle Exsertion[5/]	Grain Type[6/]	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle[7/]	Yield in gm.[8/]
IR 1108-3-5-3-2		F	4.0	1.0	241	72	4.0	2.8	1.0	0	33	4.4	75	391
(33)	LE3	3	5.3	1.3	235	59	3.8	2.0	.8	0	18	4.0	81	186
		6	4.5	1.3	243	57	3.5	2.8	.5	0	32	3.6	80	201
IR 1108-3-5-3-2		F	4.0	1.0	250	74	3.3	3.0	1.0	0	13	4.2	77	285
(34)	LE6	3	4.8	1.3	252	61	3.5	2.8	.3	0	22	4.4	76	318
		6	4.8	1.3	247	60	3.5	2.8	.3	0	12	4.0	80	282
IR 1168-24-2-1-31		F	4.0	1.0	249	74	3.0	2.0	1.3	0	13	3.8	78	277
(35)	LE3	3	6.0	1.5	241	67	3.8	1.8	1.3	2.5	17	4.5	78	138
		6	5.3	1.5	263	65	3.3	2.0	1.0	0	20	3.8	78	231
IR 1857-103-2-2		F	5.0	1.5	259	80	2.5	2.8	.3	0	10	5.3	70	464
(36)	LE3	3	4.5	1.0	264	67	3.5	2.8	.8	0	14	4.6	76	236
		6	4.5	1.0	273	65	2.5	3.0	0	0	47	4.1	78	128
IR 2004-P7-1-1		F	5.0	1.3	236	70	4.0	3.0	1.3	0	24	5.1	78	289
(37)	LE3	3	5.0	1.3	244	68	3.8	2.8	1.3	.5	42	4.3	77	291
		6	5.3	1.5	249	64	3.8	3.0	.5	0	58	4.2	79	146
IR 2068-141-3		F	4.0	1.0	239	62	3.0	3.0	1.0	0	7	3.5	75	--
(38)	LE3	3	4.8	1.3	254	63	3.3	2.0	0	0	34	3.2	69	137
		6	5.5	1.5	251	62	3.3	2.0	.3	0	43	3.3	75	36
IR 2153-26-3-5		F	4.0	1.0	243	69	3.8	2.8	2.0	0	7	3.9	75	302
(39)	LE3	3	3.8	1.0	254	65	3.3	2.0	2.0	0	27	3.5	71	294
		6	4.0	1.0	261	63	3.3	2.3	.8	0	33	3.4	70	179
PI 324 462		F	5.0	1.3	226	50	3.0	1.0	4.3	0	15	4.0	66	338
(40)		3	4.3	1.0	231	50	3.0	1.0	6.5	0	27	4.5	59	279
		6	4.5	1.0	242	49	3.0	1.3	.8	0	30	3.7	60	227

Table 1. (Continued).

Cultivar & Entry No.	Source[1]	Irrigation Treatment[2]	General Appearance[3]	Save & discard[4]	Julian Heading Date	Ht. in cm.	Panicle Exsertion[5]	Grain Type[6]	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle[7]	Yield in gm.[8]
PI 391 232		F	6.0	2.0	231	100	2.5	2.5	7.0	0	21	3.6	76	130
(41)		3	7.3	2.0	237	85	2.3	2.3	10.8	20	31	3.4	73	63
		6	7.0	2.0	241	79	3.0	2.3	5.8	42.5	34	3.1	74	44
PI 432 503		F	6.0	2.0	216	63	3.0	1.3	.5	6.3	51	5.4	84	206
(42)		3	7.3	2.0	211	58	3.3	1.5	2.8	6.3	67	3.4	83	184
		6	7.8	2.0	211	48	3.5	1.5	0	0	81	4.0	85	38
PI 433 220		F	4.3	1.0	257	74	3.8	3.0	.3	0	24	4.8	73	423
(43)		3	3.0	1.0	263	66	4.0	2.8	4.0	0	25	3.9	78	373
		6	4.0	1.0	270	59	3.5	3.0	.3	0	56	3.3	79	263
PI 432 560	HT	F	4.5	1.0	254	74	3.5	3.0	.5	0	20	4.9	69	391
(44)		3	5.0	1.3	253	64	3.3	2.5	1.5	0	24	3.6	69	234
		6	5.0	1.3	268	62	4.0	3.0	.3	0	36	3.2	69	195
PI 432 562	HT	F	4.8	1.3	246	72	3.0	3.0	1.0	0	57	3.8	63	--
(45)		3	4.8	1.3	245	61	3.3	2.5	.3	0	18	3.2	74	117
		6	5.5	1.5	257	66	3.8	2.8	.8	0	36	3.2	78	119
PI 432 564	HT	F	4.0	1.0	244	75	3.0	3.0	1.0	0	17	--	80	--
(46)		3	5.3	1.3	241	59	3.8	2.8	1.3	0	21	4.9	70	138
		6	4.3	1.0	251	49	3.8	3.0	.8	0	18	4.3	71	72
PI 432 566	HT	F	4.3	1.0	236	67	3.3	2.5	1.8	0	9	3.7	73	212
(47)		3	5.0	1.5	235	61	3.3	1.8	2.5	0	26	3.2	74	188
		6	3.8	1.0	247	55	3.3	2.3	1.0	0	28	3.2	73	189
PI 432 570	HT	F	4.8	1.3	241	57	3.8	2.0	.5	0	11	3.6	74	212
Krishna		3	4.7	1.3	240	53	4.0	1.3	0	0	25	3.5	73	155
(48)		6	5.3	1.3	250	52	3.5	2.0	0	0	42	3.4	76	140

Table 1. (Continued).

Cultivar & Entry No.	Source[1/]	Irrigation Treatment[2/]	General Appearance[3/]	Save & discard[4/]	Julian Heading Date	Ht. in cm.	Panicle Exsertion[5/]	Grain Type[6/]	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle[7/]	Yield in gm.[8/]
PI 432 572		F	5.3	1.3	240	66	3.3	2.0	.3	0	23	3.8	68	--
Pusa, 2-21		3	5.8	1.5	241	69	3.5	1.5	7.8	0	35	3.3	69	183
(49)		6	4.8	1.5	254	60	3.0	2.0	1.0	0	18	3.4	70	161
PI 432 555	HT	F	5.5	1.5	272	91	3.5	3.0	.5	5.0	52	4.0	78	208
O. glaberirna		3	5.5	1.8	271	76	3.8	2.8	1.5	0	60	4.1	79	98
(50)		6	7.3	2.0	284	68	3.8	3.0	.3	18.8	71	3.0	76	7

1/ PR = 1979 blanking study; HT = 1979 heat tolerance study; LE = 1979 intermittent irrigation study with F = flood and 3, 6, and 9 = days between irrigations, respectively.
2/ F = continuous flood; 3 and 6 = days between irrigations, respectively.
3/ 1 = good; 5 = average; 9 = poor.
4/ 1 = save; 2 = discard.
5/ 1 = well exserted; 2 = moderately well exserted; 3 = just exserted; 4 = partially exserted.
6/ 1 = short; 2 = medium; 3 = long; 4 = extra long.
7/ Degrees from horizontal, o = horizontal, 90 = vertical.
8/ To convert yield to kg/hectare (lbs/acre), multiply by a factor of 13.4 (12).

Cultivar or Entry No.	Source[1]	Irrigation Treatment[2]	Ger Appear-ance[3]	Save dis-card[4]	J Heading Date	Ht. in cm.	Panicle Exertion[5]	Grain Type[6]	Percent Lodging	Pe Sterile Panicles (white)	Percent Blanking	per 200 Seeds	Percent Stem Angle[7]	Yield in gm.[8]
Al Nam-	PR	F	6.0	2.0	221	50	4.0	2.0	0	0	26		61	137
Tsar		3	6.3	2.0	220	41	4.0	1.8	0	0	26		60	69
(1)		6	6.0	2.0	241	31	4.0	1.8	.5	0	97		61	4
IR 22	LEF	F	3.8	1.0	257	67	3.8	3.0	1.0	0	15	4.3	76	418
(2)		3	3.3	1.0	261	58	3.5	3.0	.3	0	28	3.4	78	299
		6	6.0	1.8	274	49	3.5	2.0	.3	5.0	76	3.2	74	29
IR 22	LE3	F	4.0	1.0	256	68	4.0	2.8	1.0	0	20	4.2	73	404
(3)		3	4.3	1.0	263	57	3.8	3.0	0	0	25	3.5	74	303
		6	5.0	1.0	277	49	3.8	2.3	0	0	69	3.1	79	31
IR 22	LE6	F	3.8	1.0	255	65	3.5	3.0	.8	0	15	4.0	78	410
(4)		3	4.0	1.0	262	56	4.0	3.0	.5	0	29		73	211
		6	5.0	1.0	272	49	3.3	1.8	0	0	75	3.0	74	55
IR 26		F	5.0	1.3	256	66	4.0	2.3	1.3	0	7		74	262
(5)		3	5.3	1.3	264	61	3.8	2.5	.8	0	28		73	218
		6	7.0	2.0	280	44	3.3	2.3	0	0	63		68	9
IV 213	LEF	F	4.5	1.3	249	59	2.8	2.0	1.0	0	19	4.5	79	220
(6)		3	3.8	1.0	249	57	3.3	2.0	1.5	0	22	4.2	79	348
		6	6.8	2.0	255	52	4.0	1.5	0	12.5	69	3.2	75	39
IV 213	LE3	F	5.0	1.0	235	59	3.8	2.0	1.0	0	23	4.4	80	235
(7)		3	4.0	1.0	245	58	3.3	2.0	1.3	0	21	4.0	80	325
		6	7.0	2.0	256	48	4.0	1.5	0	30.0	84	2.9	85	36
IV 213	LE6	F	5.3	1.3	239	64	3.8	2.0	.3	0	22	4.1	80	164
(8)		3	3.5	1.0	245	57	2.5	2.0	.8	.3	19	4.0	79	332
		6	6.5	2.0	257	52	4.0	1.0	0	18.8	65	3.3	85	31

Table 2. (Continued).

Cultivar & Entry No.	Source[1]	Irrigation Treatment[2]	General Appearance[3]	Save & discard[4]	Julian Heading Date	Ht. in cm.	Panicle Exsertion[5]	Grain Type[6]	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle[7]	Yield in gm.[8]
IV 213	PR	F	4.5	1.0	237	64	3.5	2.0	1.5	0	9		78	221
(9)		3	4.0	1.0	246	52	2.3	2.0	1.5	0	--		74	335
		6	7.0	2.0	256	52	4.0	1.8	0	30.0	75		85	16
IV 213-8	LE3	F	5.0	1.3	235	59	3.8	1.8	1.3	0	11		79	234
(10)		3	4.0	1.0	245	56	3.0	2.3	1.0	0	12		79	318
		6	6.8	2.0	263	52	4.0	2.0	0	21.3	59		79	20
IV 330-1	LE3	F	4.3	1.0	242	62	3.8	2.8	1.0	0	11		68	264
(11)		3	4.0	1.0	250	59	2.8	2.8	0	0	9		69	313
		6	7.3	2.0	266	46	4.0	1.8	0	11.3	86		65	6
IV 330-1	LE9	F	5.7	1.7	249	65	3.7	2.0	.7	0	6		70	52
(12)		3	4.5	1.0	249	56	4.0	3.0	.3	0	9		65	218
		6	6.5	2.0	260	50	4.0	2.5	0	21.3	56		65	18
IV 404	LEF	F	4.0	1.0	249	65	2.5	3.0	2.5	0	15	4.8	76	295
(13)		3	4.0	1.0	255	57	3.8	2.8	1.8	0	33	4.2	73	343
		6	4.0	1.0	269	54	3.5	2.3	0	0	38	3.5	70	108
IV 404	LE3	F	4.0	1.0	247	59	3.5	3.0	2.5	0	21	4.7	71	250
(14)		3	4.0	1.0	253	57	2.5	2.8	1.3	0	26	4.4	74	326
		6	4.0	1.0	267	50	3.5	2.0	0	0	45	3.4	71	118
IV 404	LE6	F	4.3	1.0	248	59	4.0	2.3	1.5	0	25	5.2	75	203
(15)		3	4.3	1.0	251	57	3.8	3.1	0	0	17	4.2	74	278
		6	4.3	1.0	265	46	3.5	2.5	.3	0	47	3.4	69	99
IV 404-6	LE3	F	4.0	1.0	250	64	3.3	3.0	2.5	0	15		75	236
(16)		3	3.8	1.0	257	58	4.0	2.8	1.5	0	10		69	332
		6	4.5	1.0	270	49	3.0	2.0	.3	0	27		75	140

Cultivar & Entry No.	Source[1/]	Irrigation Treatment[2/]	General Appearance[3/]	Save & discard[4/]	Julian Heading Date	Ht. in cm.	Panicle Exsertion[5/]	Grain Type[6/]	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle[7/]	Yield in gm.[8/]
Calrose 76	PR	F	5.5	1.5	230	64	2.5	1.8	.3	0	28	4.8	85	174
(17)		3	6.0	1.8	225	64	3.8	2.0	1.0	0	36	4.7	84	97
		6	7.0	2.0	239	45	2.5	1.8	0	2.5	100		83	5
Chen Chun Y9		F	4.5	1.0	241	61	3.3	1.0	1.8	0	11		66	226
(18)	LE6	3	4.0	1.0	240	53	3.3	1.5	0	0	5		61	215
		6	5.8	1.8	254	38	4.0	1.0	0	0	31		64	50
DD 95	LE3	F	6.0	2.0	244	100	3.5	2.0	6.5	0	9		79	160
(19)		3	6.0	2.0	247	92	3.8	2.0	7.5	0	21		78	261
		6	6.8	2.0	267	82	3.5	2.0	20.8	61.3	100		75	18
M 7	PR	F	6.0	2.0	234	71	2.5	1.8	.8	0	19		85	174
(20)		3	5.0	1.0	245	65	3.3	2.3	.8	0	2.4		81	166
		6	6.5	-.8	253	43	3.0	1.5	0	23.8	86		80	29
M 101	PR	F	5.5	1.8	229	63	3.3	2.3	.8	0	30	4.3	71	414
(21)		3	7.3	2.0	220	49	3.0	2.3	.5	0	25	3.7	78	321
		6	6.8	2.0	226	41	3.0	2.0	0	2.5	64	3.2	75	23
Nato	LEF	F	7.3	2.0	242	83	2.5	2.0	1.3	0	16	4.2	72	220
(22)		3	7.0	2.0	238	80	3.0	2.0	.5	0	14	3.7	68	266
		6	8.0	2.0	257	74	2.0	2.0	0	5.0	80	3.4	75	19
Pokkeli	LE3	F	6.3	2.0	270	113	3.3	2.3	.3	0	32		79	123
(23)		3	7.8	2.0	283	106	3.0	2.3	.3	2.5	36		80	122
		6	8.0	2.0	299	77	4.0	2.0	0	0	129		75	—
Shioji 74	PR	F	4.8	1.0	253	69	3.5	3.0	1.0	0	8		80	296
(24)		3	4.3	1.0	257	61	3.8	2.8	2.3	0	12		79	166
		6	6.5	1.8	276	54	3.8	2.0	0	0	60		73	38

Table 2. (Continued).

Cultivar & Entry No.	Source[1/]	Irrigation Treatment[2/]	General Appear-ance[3/]	Save & dis-card[4/]	Julian Heading Date	Ht. in cm.	Panicle Exsertion[5/]	Grain Type[6/]	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle[7/]	Yield in gm.[8/]
T1	LEF	F	5.5	1.3	269	64	3.0	2.5	1.3	0			70	334
(25)		3	4.0	1.0	252	62	3.3	3.0	1.3	0			75	342
		6	6.5	2.0	274	45	3.8	1.8	0	8.8			71	115
T1	LE3	F	4.3	1.0	246	62	3.0	2.3	.8	0	30	4.3	71	414
(26)		3	7.0	1.0	253	55	3.5	2.8	.5	0	25	3.7	78	321
		6	6.5	2.0	277	50	3.8	1.8	0	2.5	64	3.2	75	23
TI	LE6	F	4.3	1.0	249	60	2.8	1.8	1.3	0	16	4.2	72	220
(27)		3	4.5	1.0	254	60	3.3	2.3	.5	0	14	3.7	68	266
		6	6.8	2.0	270	48	4.0	1.3	0	5.0	80	3.4	75	19
T1	LE9	F	5.0	1.3	265	72	3.8	3.0	.3	0	32		79	123
(28)		3	4.5	1.0	274	59	3.5	3.0	.3	2.5	36		80	122
		6	7.5	1.8	289	48	2.8	2.3	0	0	29		75	--
T 181	LE6	F	5.3	1.3	251	73	2.8	2.0	1.0	0	8		80	296
(29)		3	5.3	1.0	255	84	3.3	1.3	2.3	0	12		79	166
		6	6.3	1.8	265	55	3.5	2.3	0	0	60		73	38
IR 422-2-58		F	4.8	1.0	254	75	4.0	2.8	1.3	0			70	334
(30)	LE3	3	4.3	1.0	270	70	4.0	3.0	1.3	0			75	342
		6	5.8	1.5	278	57	4.0	3.0	0	8.8			71	115
IR 944-93-2-1-2-2		F	5.3	1.5	253	69	3.8	2.8	.3	0			71	259
(31)	LE3	3	4.0	1.0	260	61	3.5	3.0	.8	0			73	245
		6	7.0	1.8	281	54	4.0	2.3	0	25.0			74	7
IR 1108-3-5-3-2		F	4.0	1.0	244	64	3.5	3.0	.8	0	37	4.5	78	372
(32)	LEF	3	4.0	1.0	258	59	3.3	3.0	.8	0	19	4.0	80	237
		6	6.5	1.8	275	49	3.5	2.5	0	0	66	3.5	80	45

Table 2. (Continued).

Cultivar & Entry No.	Source[1/]	Irrigation Treatment[2/]	General Appearance[3/]	Save & discard[4/]	Julian Heading Date	Ht. in cm.	Panicle Exsertion[5/]	Grain Type[6/]	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle[7/]	Yield in gm.[8/]
IR 1108-3-5-3-2		F	5.3	1.5	261	62	3.0	3.0	.5	0	64	4.3	79	239
(33)	LE3	3	4.3	1.0	253	68	3.5	3.0	.8	0	19	4.2	79	301
		6	6.8	2.0	276	45	3.3	2.3	0	2.5	65	3.4	81	24
IR 1108-3-5-3-2		F	3.8	1.0	260	67	3.0	3.0	1.0	0	24	3.9	78	374
(34)	LE6	3	4.0	1.0	264	59	3.0	3.0	.3	0	39	3.8	79	247
		6	7.0	2.0	285	46	4.0	2.5	0	2.5	64	3.2	80	30
IR 1168-24-2-1-3-1		F	5.3	1.5	264	72	3.3	2.3	.5	0			75	341
(35)	LE3	3	4.3	1.0	268	69	2.8	2.0	1.5	0			78	319
		6	8.0	2.0	300	53	4.0	2.3	0	0			71	2
IR 1857-10-3-2-2		F	4.5	1.0	256	70	3.3	2.5	.3	0			74	357
(36)	LE3	3	4.8	1.3	269	60	3.0	2.5	.3	0			79	183
		6	6.8	2.0	282	47	3.8	2.0	0	5.0			79	12
IR 2004-P7-1-1		F	5.3	1.3	250	69	3.8	3.0	0	0			78	313
(37)	LE3	3	5.0	1.3	256	64	3.5	3.0	0	0			81	174
		6	6.0	2.0	260	52	3.8	2.8	0	7.5			81	18
IR 2068-141-3		F	4.5	1.0	251	71	2.8	2.3	1.3	0			78	230
(38)	LE3	3	4.5	1.0	258	63	3.0	2.3	.5	0			79	246
		6	6.8	2.0	277	55	3.5	1.5	0	18			80	16
IR 2153-26-3-5		F	4.0	1.0	259	64	3.3	3.0	2.8	0			80	269
(39)	LE3	3	4.0	1.0	264	55	3.5	2.5	1.0	0			73	228
		6	6.3	1.8	279	50	3.3	2.0	0	21.3			78	22
PI 324 462		F	5.0	1.3	239	54	3.5	1.0	0	0			63	295
(40)		3	4.8	1.0	239	52	3.3	1.5	.5	0			60	322
		6	6.0	1.8	253	37	4.0	1.0	0	0			66	59

Table 2. (Continued).

Cultivar & Entry No.	Source 1/	Irrigation Treatment 2/	General Appear-ance 3/	Save & dis-card 4/	Julian Heading Date	Ht. in cm.	Panicle Exsertion 5/	Grain Type 6/	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle 7/	Yield in gm. 8/
PI 391 232		F	5.5	1.5	244	85	2.8	2.3	6.5	0			75	264
(41)		3	6.0	2.0	245	94	3.0	2.0	7.5	0			80	216
		6	7.0	2.0	259	80	2.8	1.5	1.8	60			75	20
PI 432 503		F	6.0	2.0	228	66	2.3	1.0	0	12.5			85	209
(42)		3	7.0	2.0	225	57	3.0	1.5	0	10.0			83	100
		6	7.3	2.0	233	28	3.3	1.8	0	17.5			75	5
PI 433 220		F	3.5	1.0	240	69	3.8	3.0	2.0	0	38	4.7	73	428
(43)		3	4.0	1.0	273	64	3.5	3.0	.5	0	54	3.9	76	354
		6	5.8	1.8	284	47	5.8	3.0	0	2.5	45	3.6	78	29
PI 432 560	HT	F	5.0	1.0	260	70	4.0	3.0	.5	0	20	4.0	74	307
(44)		3	3.5	1.0	265	63	4.0	3.0	1.3	0	50	3.7	76	324
		6	5.3	1.0	210	50	3.8	2.0	0	7.5	83	2.9	71	17
PI 432 562	HT	F	4.5	1.0	250	68	3.0	3.0	1.3	0			76	247
(45)		3	4.0	1.0	257	63	3.8	3.0	.8	0			79	294
		6	7.5	2.0	275	60	4.0	3.0	0	28.8			78	11
PI 432 564	HT	F	4.5	1.0	253	64	3.3	3.0	1.0	0	10	5.3	75	170
(46)		3	4.3	1.0	258	56	4.0	3.0	0	0	22	4.5	68	158
		6	6.3	1.8	275	45	3.8	2.8	0	0	65	2.8	74	21
PI 432 566	HT	F	4.8	1.0	241	67	3.3	2.3	2.5	0	17	4.6	74	233
(47)		3	3.8	1.0	246	60	3.0	2.3	1.3	0	21	3.4	71	248
		6	5.5	1.3	267	44	3.8	2.0	0	0	51	2.7	69	35
PI 432 570	HT	F	5.3	1.5	246	53	3.8	1.8	0	0			71	185
Krishna		3	4.3	1.0	252	53	3.5	1.8	0	0			71	242
(48)		6	7.0	2.0	270	43	4.0	1.8	.3	10.0			75	2

Cultivar or entry No.	Source1/	Irrigation Treatment2/	Gene Appear-ance3/	Save & dis-card4/	Jul... Heading Date	Ht. in cm.	Panicle Exsertion5/	Grain Type6/	Percent Lodging	Per... Sterile Panicles (white)	Percent Blanking	per 200 Seeds	Percent Stem Angle7/	Yield in gm.8/
PI 432 572		F	4.5	1.0	250	61	3.3	1.8	.5	0			73	132
Pusa, 2-21		3	3.8	1.0	256	63	3.0	2.0	.8	0			68	343
(49)		6	5.5	1.5	270	50	3.5	1.5	0	7.5			71	35
PI 432 555	HT	F	5.5	1.5	280	85	3.3	3.0	.8	0			78	183
O. glaberirna		3	6.5	1.8	280	73	3.0	3.0	1.0	25.0			80	29
(50)		6	8.0	2.0	291	55	4.0	3.0	0	7.5			76	3

1/ PR = 1979 blanking study; HT = 1979 heat tolerance study; LE = 1979 intermittent irrigation study with F = flood and 3, 6, and 9 = days between irrigations, respectively.
2/ F = continuous flood; 3 and 6 = days between irrigations, respectively.
3/ 1 = good; 5 = average; 9 = poor.
4/ 1 = save; 2 = discard.
5/ 1 = well exserted; 2 = moderately well exserted; 3 = just exserted; 4 = partially exserted.
6/ 1 = short; 2 = medium; 3 = long; 4 = extra long.
7/ Degrees from horizontal, o = horizontal, 90 = vertical.
8/ To convert yield to kg/hectare (lbs/acre), multiply by a factor of 13.4 (12).

Table 3. Intermittent rice irrigation experiment-advanced cultivars, planted on June 19, 1981 (Julian Date 170) at El Centro, California.

Cultivar & Entry No.	Source 1/	Irrigation Treatment 2/	General Appear-ance 3/	Save & dis-card 4/	Julian Heading Date	Ht. in cm.	Panicle Exsertion 5/	Grain Type 6/	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle 7/	Yield in gm. 8
Al Nam-	PR	F	5.3	1.3	248	57	3.3	1.3	1.3	0			67	150
Tsar		3	5.3	1.3	244	41	3.3	2.0	0	0			63	42
(1)		6	6.0	2.0	251	37	3.5	1.5	0	0			61	14
IR 22	LE6	F	4.3	1.0	271	72	3.5	2.8	1.0	0	37	3.9	76	246
(2)		3	5.3	1.3	278	63	3.3	3.0	.3	0	64	3.9	80	110
		6	7.5	2.0	293	43	4.0	2.5	0	5.1			74	17
IR 26	LE3	F	5.3	1.3	276	74	3.7	2.3	1.3	0	51	4.4	78	177
(3)		3	6.5	2.0	284	66	4.0	2.3	0	0	81	3.5	80	39
		6	8.0	2.0	303	47	4.0	2.0	0	0			75	3
IV 213	LE6	F	4.3	1.0	253	61	3.7	2.0	1.3	0	27	4.4	78	256
(4)		3	5.3	1.3	258	58	4.0	1.8	.8	0	32.5	4.1	80	132
		6	6.8	2.0	269	56	4.0	1.8	0	25			85	38
IV 330-1	LE9	F	5.3	1.3	262	57	4.0	3.0	1.7	0			70	
(5)		3	5.8	1.8	271	54	4.0	2.5	0	0			71	
		6	7.5	2.0	281	56	4.0	3.0	0	21.3			69	
IV 404	LE6	F	5.5	1.8	265	60	4.0	2.5	1.3	0	36	4.4	70	231
(6)		3	4.3	1.0	265	56	4.0	3.0	.8	0	37	4.1	68	120
		6	4.8	1.0	272	56	4.0	2.8	0	0			70	96
Calrose 76	PR	F	6.3	2.0	249	66	1.3	1.3	.7	0	10	5.3	85	
(7)		3	6.3	2.0	248	53	1.5	2.0	.3	0	42	4.2	83	31
		6	6.5	2.0	256	46	2.8	1.5	0	0			84	1
M 7	PR	F	6.0	2.0	251	63	1.0	1.8	.3	0	39		83	217
(8)		3	6.5	2.0	253	51	1.5	1.8	.3	0	52		85	31
		6	6.3	2.0	258	52	2.8	2.0	0	18.8			85	5

Table [illegible]. (Continued).

Cultivar & Entry No.	Source1/	Irrigation Treatment2/	General Appear-ance3/	Save & dis-card4/	Julian Heading Date	Ht. in cm.	Panicle Exsertion5/	Grain Type6/	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle7/	Yield in gm.8/
M 101	PR	F	6.0	2.0	251	54	2.5	1.8	.5	0			84	
(9)		3	6.3	2.0	243	52	2.5	2.0	0	6.3			83	38
		6	6.0	2.0	252	45	2.5	2.0	0	6.3			81	9
Nato	LEF	F	6.3	2.0	256	103	1.7	2.0	0	33.3	23	4.3	81	20
(10)		3	7.0	2.0	265	83	1.0	2.0	.5	72.5	81	3.9	85	1
		6	7.0	2.0	274	84	1.5	2.0	0	68.8	--	--		
T 1	LE6	F	5.0	1.0	269	64	4.0	1.3	1.8	0			70	159
(11)		3	5.5	1.5	275	58	4.0	1.3	0	0			75	70
		6	7.3	2.0	294	48	4.0	1.0	0	2.5			71	11
T 181	LE6	F	6.3	2.0	261	74	2.5	1.0	.3	0			83	269
(12)		3	5.5	1.8	262	64	3.3	1.5	.3	0			74	55
		6	6.5	2.0	268	63	3.0	1.3	.8	17.5			79	24
IR 442-2-58		F	5.0	1.0	273	79	4.0	3.0	2.0	0	20		74	270
(13)	LE3	3	4.8	1.0	278	71	4.0	2.8	.8	0	35		74	157
		6	6.8	2.0	290	57	4.0	3.0	0	0	--		74	40
IR 944-93-2-1-2-2		F	5.5	1.5	260	67	3.8	3.0	1.3	0	40		75	211
(14)	LE3	3	5.5	1.5	279	63	3.5	2.8	.3	0	61		75	63
		6	7.3	2.0	291	51	4.0	2.5	0	2.5	--		75	40
IR 1108-3-5-3-2		F	5.3	1.3	275	73	3.3	3.0	1.3	0	54	4.1	76	170
(15)	LE6	3	7.5	2.0	293	49	3.8	2.8	0	0	43	4.2	83	47
		6	8.0	2.0	318	42	4.0	2.5	0	0	--	--	80	2
IR 1168-24-2-1-3-1		F	6.5	2.0	283	72	3.3	2.0	.3	0			75	20
(16)	LE3	3	7.3	2.0	289	59	3.5	2.0	0	0			75	40
		6	8.0	2.0	308	55	4.0	2.3	0	0			77	2

Table 3. (Continued).

Cultivar & Entry No.	Source1/	Irrigation Treatment2/	General Appear-ance3/	Save & dis-card4/	Julian Heading Date	Ht. in cm.	Panicle Exsertion5/	Grain Type6/	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle7/	Yield in gm.8/
IR 1857-103-2-2		F	5.3	1.3	277	75	3.3	2.3	.7	0			73	236
(17)	LE3	3	6.3	1.8	284	59	3.8	3.0	.3	0			79	78
		6	7.5	2.0	277	47	4.0	2.5	0	2.5			78	13
IR 2004-P7-1-1		F	5.5	1.5	268	72	3.8	3.0	.3	0			78	289
(18)	LE3	3	6.3	1.8	275	64	3.8	3.0	0	0			83	55
		6	7.3	2.0	286	58	4.0	3.0	0	8.8			80	7
IR 2068-141-3		F	5.3	1.3	271	78	3.0	1.7	.3	0			78	183
(19)	LE3	3	6.0	1.8	280	64	3.5	2.0	0	0			81	57
		6	8.0	2.0	297	51	4.0	1.8	0	5.0			80	7
IR 2153-26-3-5		F	5.0	1.0	276	75	3.8	3.0	.8	0			78	212
(20)	LE3	3	5.0	1.0	280	65	3.5	3.0	.3	0			79	97
		6	7.5	2.0	296	48	4.0	2.3	0	2.5			75	7
PI 324 462		F	4.5	1.0	261	65	3.0	1.0	1.0	0			66	369
(21)		3	4.8	1.0	268	53	3.0	1.0	.3	0			70	138
		6	5.3	1.3	273	51	3.5	1.0	0	0			69	79
PI 391 232		F	5.3	1.3	258	100	3.0	2.0	3.7	0			73	313
(22)		3	5.5	1.5	266	96	2.5	2.0	11.0	5.0			75	84
		6	7.0	2.0	275	92	1.0	2.0	1.8	75.0			76	23
PI 432 560	HT	F	4.8	1.3	267	71	3.8	3.0	.5	0			75	254
(23)		3	6.0	1.8	277	67	3.3	3.0	.5	6.3			80	70
		6	6.5	2.0	286	54	4.0	3.0	0	2.5			74	24
PI 432 566	HT	F	4.0	1.0	259	73	3.7	2.3	3.0	0			78	283
(24)		3	4.3	1.3	264	60	3.5	2.5	1.5	0			76	99
		6	5.8	1.5	271	56	3.8	2.3	0	5.0			75	33

Table 3. (Continued).

Cultivar & Entry No.	Source[1/]	Irrigation Treatment[2/]	General Appearance[3/]	Save & discard[4/]	Julian Heading Date	Ht. in cm.	Panicle Exsertion[5/]	Grain Type[6/]	Percent Lodging	Percent Sterile Panicles (white)	Percent Blanking	Wt. per 200 Seeds	Percent Stem Angle[7/]	Yield in gm.[8/]
PI 432 555	HT	F	6.3	2.0	278	86	3.8	3.0	0	2.5	66		78	117
O. glaberirna		3	7.0	2.0	287	63	4.0	3.0	0	0	81		80	25
(25)		6	8.3	2.0	297	51	4.0	2.8	0	5.0			76	3

1/ PR = 1979 blanking study; HT = 1979 heat tolerance study; LE = 1979 intermittent irrigation study with F = flood and 3, 6, and 9 = days between irrigations, respectively.
2/ F = continuous flood; 3 and 6 = days between irrigations, respectively.
3/ 1 = good; 5 = average; 9 = poor.
4/ 1 = save; 2 = discard.
5/ 1 = well exserted; 2 = moderately well exserted; 3 = just exserted; 4 = partially exserted.
6/ 1 = short; 2 = medium; 3 = long; 4 = extra long.
7/ Degrees from horizontal, o = horizontal, 90 = vertical.
8/ To convert yield to kg/hectare (lbs/acre), multiply by a factor of 13.4 (12).

Table 4. Average soil salinity measurements in EC of mmho/cm before and after the irrigation experiments for three irrigation and three planting date treatments at El Centro, California, in 1980.

Irrig. Treat-ment	Plant-ing Date	0 to 30-cm Soil Depth		Difference		30 to 60-cm Soil Depth		Difference	
		Before Irrigation	After Irrigation	mmho/cm and %		Before Irrigation	After Irrigation	mmho/cm and %	
Flood	4/17	4.47	3.01	1.46	33%	4.85	4.33	.52	11%
3 day	4/17	3.99	1.80	2.19	55%	3.39	2.00	1.39	41%
6 day	4/17	3.09	1.77	1.32	43%	2.76	2.66	.10	4%
Flood	5/15	3.27	2.15	1.12	34%	3.24	2.57	.67	21%
3 day	5/15	2.65	1.45	1.20	45%	2.49	1.54	.95	38%
6 day	5/15	2.26	1.39	.87	38%	2.20	1.53	.67	30%
Flood	6/17	5.86	2.86	3.00	51%	5.20	3.24	1.96	38%
3 day	6/17	3.36	1.55	1.81	54%	2.69	1.44	1.25	45%
6 day	6/17	3.19	1.46	1.73	54%	2.80	1.67	1.13	40%

Table 5. Summary of seasonal water applied, precipitation, and pan evaporation for three irrigation treatments and four planting dates at Yuma, Arizona, 1981.

Factor	Irrigation Treatment 1/	Planting Dates March 4	April 1	April 29	May 27
Number of Irrigations	2/wk	48	43	40	36
	1/wk	30	28	25	24
	10 days	25	21	22	18
Seasonal Irrigation Water Applied (cm)	2/wk	422	327	343	355
	1/wk	229	216	220	246
	10 days	221	171	184	199
Average Irrigation Size (cm)	2/wk	8.8	7.6	8.6	9.8
	1/wk	7.6	7.7	8.8	10.3
	10 days	8.8	8.1	8.4	11.0
Seasonal Precipitation (cm)	All Irrig. Trts.	2.1	0.8	0.8	0.8
Seasonal Total Water Applied (cm)	2/wk	424	328	344	356
	1/wk	231	217	221	247
	10 days	223	172	185	200
Seasonal Pan Evaporation (cm)	All Irrig. Trts.	230	212	172	171

1/ Irrigation water was applied either twice a week, once a week, or every 10 days.

Table 6. Intermittent rice irrigation experiment planted on March 4, 1981 (Julian Date 63) at Yuma, Arizona.

Cultivar and Entry No.	Irrigation Treatment 1/	Julian Heading Date	Plant Height in cm.	Grain Type 2/	Panicle Exsertion 3/	Percent Lodging	Wt. Per 500 seeds	Stem Angle 4/	Yield in kg/ha
IV 404	2/wk	226	64	3.0	3.0	0	12.0	3.0	5020
(1)	1/wk	237	48	3.5	4.0	0	12.4	3.0	2139
	10	246	38	--	--	0	--	--	-- *
IV 213	2/wk	204	61	3.0	4.0	0	11.5	2.5	5730
(2)	1/wk	237	48	--	--	0	--	--	--
	10	246	41	--	--	0	--	--	--
IR 22	2/wk	233	64	3.0	4.0	0	9.4	2.0	5297
(3)	1/wk	237	43	2.5	5.0	0	10.8	2.0	761
	10	251	43	--	--	0	--	--	--
IR 1108-3-5-	2/wk	212	61	3.0	4.0	0	11.4	2.5	4919
3-2	1/wk	237	51		5.5	0	8.8	1.0	1157
(4)	10	246	43		--	0	--	--	--
Taichung	2/wk	251	89	3.0	4.5	0	11.4	1.0	931
181	1/wk	251	69	--	--	0	--	--	--
(5)	10	257	64	--	--	0	--	--	--
IV 330-1	2/wk	211	64	4.0	5.0	0	10.9	3.8	4661
(6)	1/wk	237	43	--	--	0	--	--	--
	10	216	41	--	--	0	--	--	--

1/ 2/wk = twice weekly irrigations; 1/wk = weekly irrigations; 10 = days between irrigations, respectively.
2/ 1 = pearl; 2 = short (5.5 mm or less); 3 = medium (5.51-6.6 mm); 4 = long (6.61-7.5 mm); 5 = extra long (> 7.51 mm).
3/ 1 = well exserted; 3 = moderately well exserted; 5 = just exserted; 7 = partly exserted; 9 = enclosed.
4/ 1 = erect; 2 = angle is about 30° from the perpendicular; 3 = angle is about 45° from the perpendicular.
* No harvest because of considerable variability or negligible yield.

Table 7. Intermittent rice irrigation experiment planted on April 1, 1981 (Julian Date 91) at Yuma, Arizona.

Cultivar and Entry No.	Irrigation Treatment 1/	Julian Heading Date	Plant Height in cm.	Grain Type 2/	Panicle Exsertion 3/	Percent Lodging	Wt. per 500 Seeds	Stem Angle 4/	Yield in kg/ha
IV 404	2/wk	247	58	3.5	5.5	0	10.4	1.0	3499
(1)	1/wk	251	41	---	---	0	---	---	--- *
	10	257	31	---	---	0	---	---	---
IV 213	2/wk	226	56	3.0	6.0	0	11.1	1.0	3619
(2)	1/wk	247	41	---	---	0		---	---
	10	247	38	---	---	0		---	---
IR 22	2/wk	247	61	3.0	5.0	0	10.1	1.0	3264
(3)	1/wk	247	38	---	---	0		---	---
	10	264	36	---	---	0		---	---
IR 1108-3-5-	2/wk	247	51	3.0	6.0	0	10.1	1.0	2240
3-2	1/wk	247	36	---	---	0		---	---
(4)	10	245	36	---	---	0		---	---
Taichung	2/wk	247	79	3.0	3.0	0	10.5	1.0	373
181	1/wk	264	58	---	---	0		---	---
(5)	10	271	51	---	---	0		---	---
IV 330-1	2/wk	226	48	3.0	6.0	0	12.4	1.0	3102
(6)	1/wk	247	41	---	---	0		---	---
	10	251	36	---	---	0		---	---

1/ 2/wk = twice weekly irrigations; 1/wk = weekly irrigations; 10 = days between irrigations, respectively.
2/ 1 = pearl; 2 = short (5.5 mm or less); 3 = medium (5.51-6.6 mm); 4 = long (6.61-7.5 mm); 5 = extra long (> 7.51 mm).
3/ 1 = well exserted; 3 = moderately well exserted; 5 = just exserted; 7 = partly exserted; 9 = enclosed.
4/ 1 = erect; 2 = angle is about 30° from the perpendicular; 3 = angle is about 45° from the perpendicular.
* No harvest because of considerable variability or negligible yield.

Table 8. Intermittent rice irrigation experiment planted on April 29, 1981 (Julian Date 119) at Yuma, Arizona.

Cultivar and Entry No.	Irrigation Treatment 1/	Julian Heading Date	Plant Height in cm.	Grain Type 2/	Panicle Exsertion 3/	Percent Lodging	Wt. Per 500 Seeds	Stem Angle 4/	Yield in kg/ha
IV 404	2/wk	247	51	4.0	5.3	0	11.8	1.5	4393
(1)	1/wk	257	38	3.0	7.0	0	11.1	1.5	1157
	10	260	31	--	--	0		--	-- *
IV 213	2/wk	240	56	3.0	6.5	0	11.0	1.0	2817
(2)	1/wk	251	41	3.0	7.0	0	10.2	1.0	438
	10	257	38	--	--	0		--	--
IR 22	2/wk	251	58	4.0	6.0	0	10.9	1.5	5168
(3)	1/wk	257	38	3.0	7.0	0	11.2	1.0	613
	10	257	33	--	--	0		--	--
IR 1108-3-5-	2/wk	247	53	4.0	5.5	0	11.6	1.0	5025
3-2	1/wk	257	38	3.0	7.0	0	9.9	1.0	1019
(4)	10	250	33	--	--	0		--	--
Taichung	2/wk	247	81	3.0	1.5	0	11.9	1.0	1604
181	1/wk	260	58		--	0		--	--
(5)	10	250	46		--	0		--	--
IV 330-1	2/wk	247	58	3.5	5.5	0	12.4	1.0	2139
(6)	1/wk	251	33	3.0	6.0	0	11.4	1.0	484
	10	257	36	--	--	0		--	--

1/ 2/wk = twice weekly irrigations; 1/wk = weekly irrigations; 10 = days between irrigations, respectively.
2/ 1 = pearl; 2 = short (5.5 mm or less); 3 = medium (5.51-6.6 mm); 4 = long (6.61-7.5 mm); 5 = extra long (>7.51 mm).
3/ 1 = well exserted; 3 = moderately well exserted; 5 = just exserted; 7 = partly exserted; 9 = enclosed.
4/ 1 = erect; 2 = angle is about 30° from the perpendicular; 3 = angle is about 45° from the perpendicular.
* No harvest because of considerable variability or negligible yield.

Table 9. Intermittent rice irrigation experiment planted on May 27, 1981 (Julian Date 147) at Yuma, Arizona.

Cultivar and Entry No.	Irrigation Treatment 1/	Julian Heading Date	Plant Height in cm.	Grain Type 2/	Panicle Exsertion 3/	Percent Lodging	Wt. Per 500 Seeds	Stem Angle 4/	Yield in kg/ha
IV 404	2/wk	247	43	4.0	6.0	0	12.9	1.0	3900
(1)	1/wk	260	31	3.0	7.0	0	10.8	1.0	1176
	10	250	31	—	—	0	—	—	— *
IV 213	2/wk	247	43	3.0	6.0	0	11.8	1.0	959
(2)	1/wk	254	31	—	—	0	—	—	—
	10	257	31	—	—	0	—	—	—
IR 22	2/wk	257	46	4.0	6.0	0	11.1	1.0	3421
(3)	1/wk	271	33	4.0	7.0	0	9.3	1.0	834
	10	271	31	—	—	0	—	—	—
IR 1108-3-5-	2/wk	247	38	4.0	6.5	0	11.0	1.0	3563
3-2	1/wk	260	31	3.0	6.0	0	10.3	1.0	2250
(4)	10	271	33	—	—	0	—	—	—
Taichung	2/wk	251	69	3.0	6.0	0	11.4	1.0	1153
181	1/wk	260	53	—	—	0	—	—	—
(5)	10	271	43	—	—	0	—	—	—
IV 330-1	2/wk	247	46	—	—	0	—	—	—
(6)	1/wk	254	33	—	—	0	—	—	—
	10	257	31	—	—	0	—	—	—

1/ 2/wk = twice weekly irrigations; 1/wk = weekly irrigations; 10 = days between irrigations, respectively.
2/ 1 = pearl; 2 = short (5.5 mm or less); 3 = medium (5.51-6.6 mm); 4 = long (6.61-7.5 mm); 5 = extra long (>7.51 mm).
3/ 1 = well exserted; 3 = moderately well exserted; 5 = just exserted; 7 = partly exserted; 9 = enclosed.
4/ 1 = erect; 2 = angle is about 30° from the perpendicular; 3 = angle is about 45° from the perpendicular.
* No harvest because of considerable variability or negligible yield.

Table 10. Average and range of leaf analysis on rice for three growth stages and grain nutrient analysis at harvest for four planting dates at Yuma, Arizona, 1981.

Planting Date	Leaf Analysis - Days Since Planting: 50			65			80			Composite of 50, 65, & 80				Nutrient Analysis for Harvested Rice						
	N	PO_4-P	K	N	PO_4-P	K	N	PO_4-P	K	Fe	Zn	Mn	Cu	N*	K	P	Fe	Mn	Zn	Cu
	(%)	(ppm)	(%)	(%)	(ppm)	(%)	(%)	(ppm)	(%)	(ppm)				(%)			(ppm)			
Mar 4																				
avg.	4.3	1240	2.1	3.3	1140	2.0	3.0	1000	1.4	175	51	31	18	2.2	2.3	0.21	118	28	37	21
Range-																				
low	3.6	950	1.6	2.8	950	1.5	2.8	850	1.1	98	38	20	14	2.1	2.0	0.16	108	22	28	18
high	4.8	1650	2.6	3.8	1500	2.4	3.3	1250	1.8	288	74	38	22	2.4	2.6	0.30	126	34	44	26
Apr 1																				
avg.	4.0	1450	1.9	3.4	1340	2.0	3.0	1160	1.8	119	36	35	16	2.2	2.3	0.19	129	31	44	25
Range-																				
low	3.6	1100	1.5	3.0	1100	1.8	2.7	900	1.6	87	18	28	10	1.8	2.2	0.16	126	30	40	23
high	4.4	1800	2.1	3.8	1550	2.3	3.3	1400	2.1	184	48	40	22	2.4	2.5	0.22	140	34	48	28
Apr 29																				
avg.	3.9	1240	1.9	4.2	1270	2.1	3.4	1570	1.8	242	35	26	15	2.2	2.6	0.20	123	34	56	22
Range-																				
low	3.0	850	1.5	3.6	850	1.8	3.0	900	1.4	146	27	18	12	2.1	2.3	0.14	108	30	48	12
high	4.5	1700	2.2	4.6	1750	2.3	3.8	2600	2.1	382	66	34	20	2.4	2.7	0.24	132	38	62	30
May 27																				
avg.	2.9	1540	1.7	3.7	1460	2.2	3.0	890	1.6	116	38	34	11	2.2	2.4	0.22	118	32	58	25
Range-																				
low	2.6	1000	1.2	3.0	900	1.7	2.4	650	1.3	78	26	26	6	1.8	2.2	0.18	108	22	54	22
high	3.5	2400	2.2	4.3	2200	2.6	3.9	1200	2.0	184	54	44	15	2.3	2.6	0.24	132	38	62	30

* Percent protein = N x 6.25.

Table 11. Summary of rice yields from the observational nursery planted on four dates at Yuma, Arizona. 1/

Cultivar	Entry No.	Grams/plot 2/ Mar 4	Apr 1	Apr 29	May 27
M 101	(1)	229.7	304.9	75.0	12.8
Calrose 76	(2)	445.9	272.9	80.7	3.8
IR 28	(3)	521.0	141.7	325.0	Not planted
IV 404-6	(4)	948.1	592.9	962.3	Not planted
IV 56	(5)	226.2	200.4	395.4	Not planted
M 7	(6)	151.7	123.0	299.1	29.8
IR 442-2-58	(7)	98.8	185.4	841.8	706.1
PI 362 SI 364	(8)	130.8	138.5	397.1	73.4
IR 528 PK 13 E1	(9)	937.4	942.0	806.4	863.1
IR 2268-24-2-3-1	(10)	884.4	754.1	1129.4	875.1
Shioji 74	(11)	584.7	451.4	649.4	725.2
IV 404-5	(12)	567.7	454.0	468.6	865.2
Kar 27	(13)	815.2	609.4	766.5	625.6
PI 432 566	(14)	454.5	305.8	772.7	481.3
Chu Chinisao, China	(15)	236.3	363.6	526.2	337.4
PI 433 220	(16)	254.8	341.4	797.2	427.9
PI 432 560	(17)	944.6	504.4	1239.9	1051.1
Kar 30	(18)	1127.0	737.8	832.4	850.0
T 1	(19)	569.0	265.6	1041.2	942.2
PI 402 RP 414	(20)	806.9	373.3	810.3	975.4
HZ ROS 637	(21)	552.7	457.2	969.2	664.1
IR 2153-26-3-5	(22)	127.4	100.3	576.7	412.1
IR 2004-P7-1-1	(23)	159.9	299.0	966.8	482.3
IR 1857-103-2-2	(24)	37.5	202.0	614.5	208.1
PI 403 RP 7923	(25)	1082.1	620.9	1100.9	802.2
IR 944-93-2-1-2-2	(26)	841.2	386.0	1009.8	817.3
IV 404	(27)	637.2	479.3	1007.2	949.8
IV 213	(28)	811.0	575.5	1148.7	946.1
IR 22	(29)	356.0	386.1	1134.6	864.2
IR 1108-3-5-3-2	(30)	520.0	382.5	1134.0	799.9
IV 330-1	(31)	326.2	580.4	563.8	244.2
Taichung 181	(32)	21.9	100.6	187.9	171.7

1/ Irrigation water was applied twice a week on all nursery plots.
2/ Multiply by 7.7 (6.9) to obtain kg/hectare (lbs/acre).

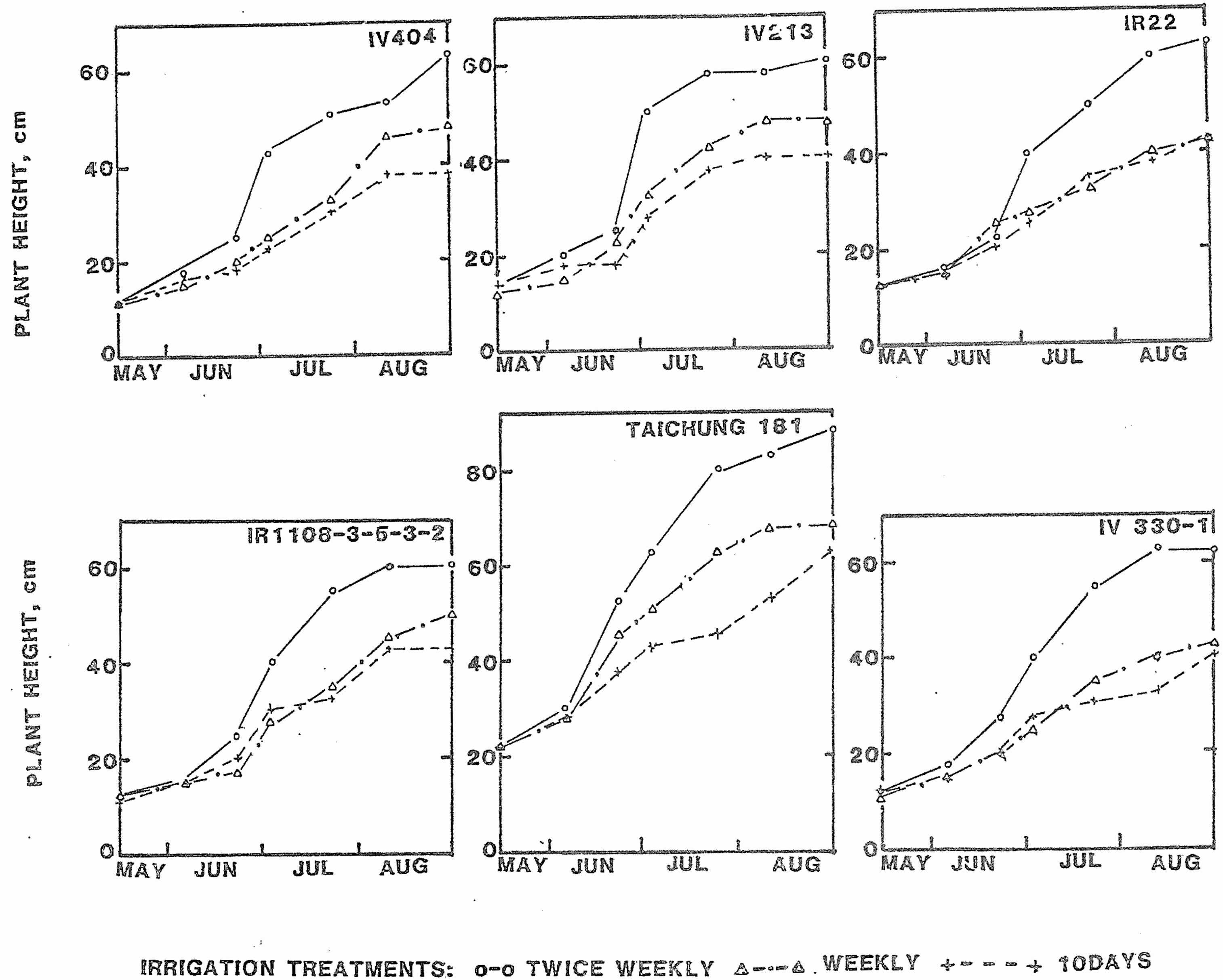

Figure 1. Effects of three irrigation treatments on plant growth for six rice cultivars planted at Yuma, Arizona, on March 4, 1981.

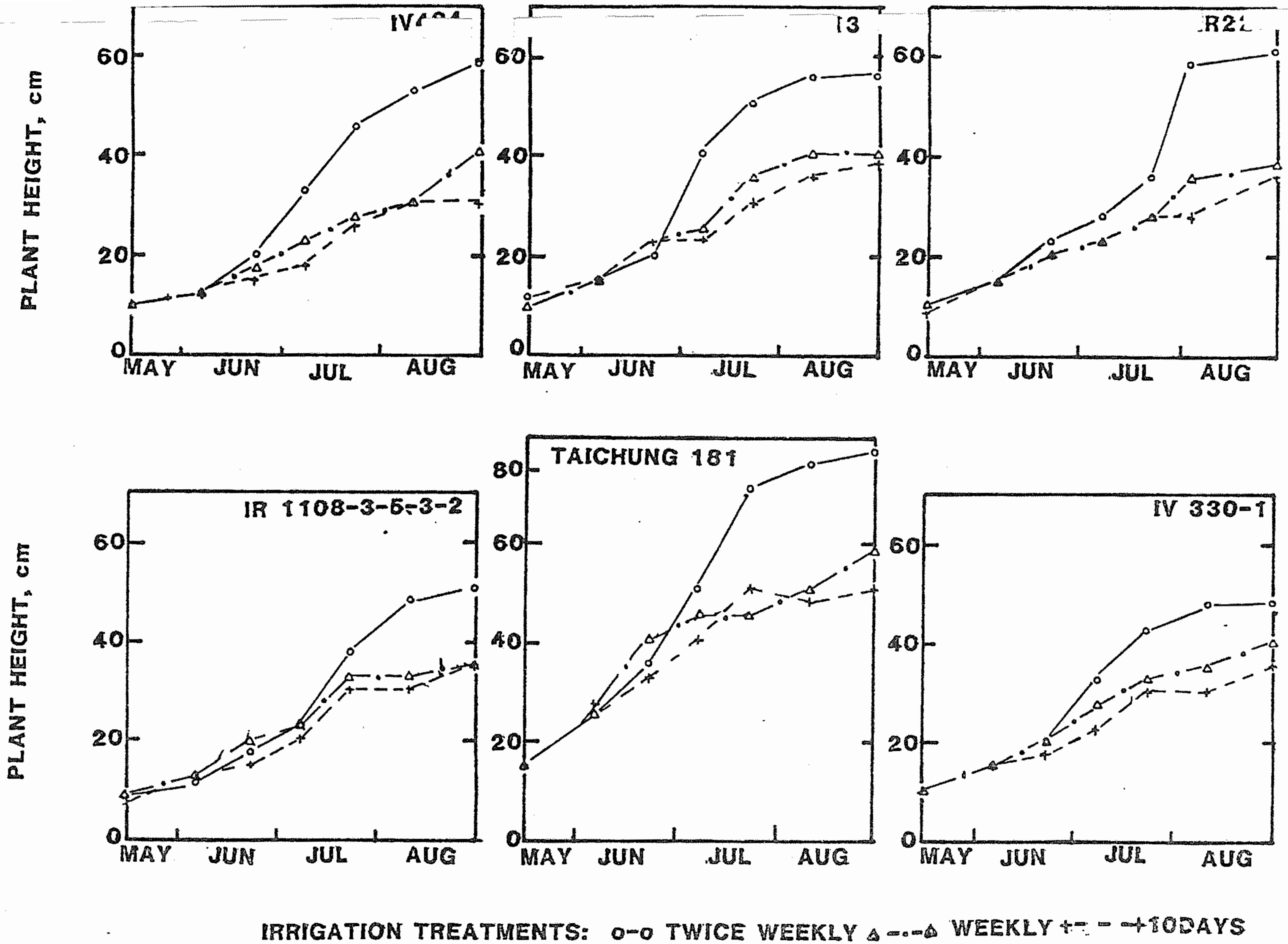

Figure 2. Effects of three irrigation treatments on plant growth for six rice cultivars planted at Yuma, Arizona, on April 1, 1981.

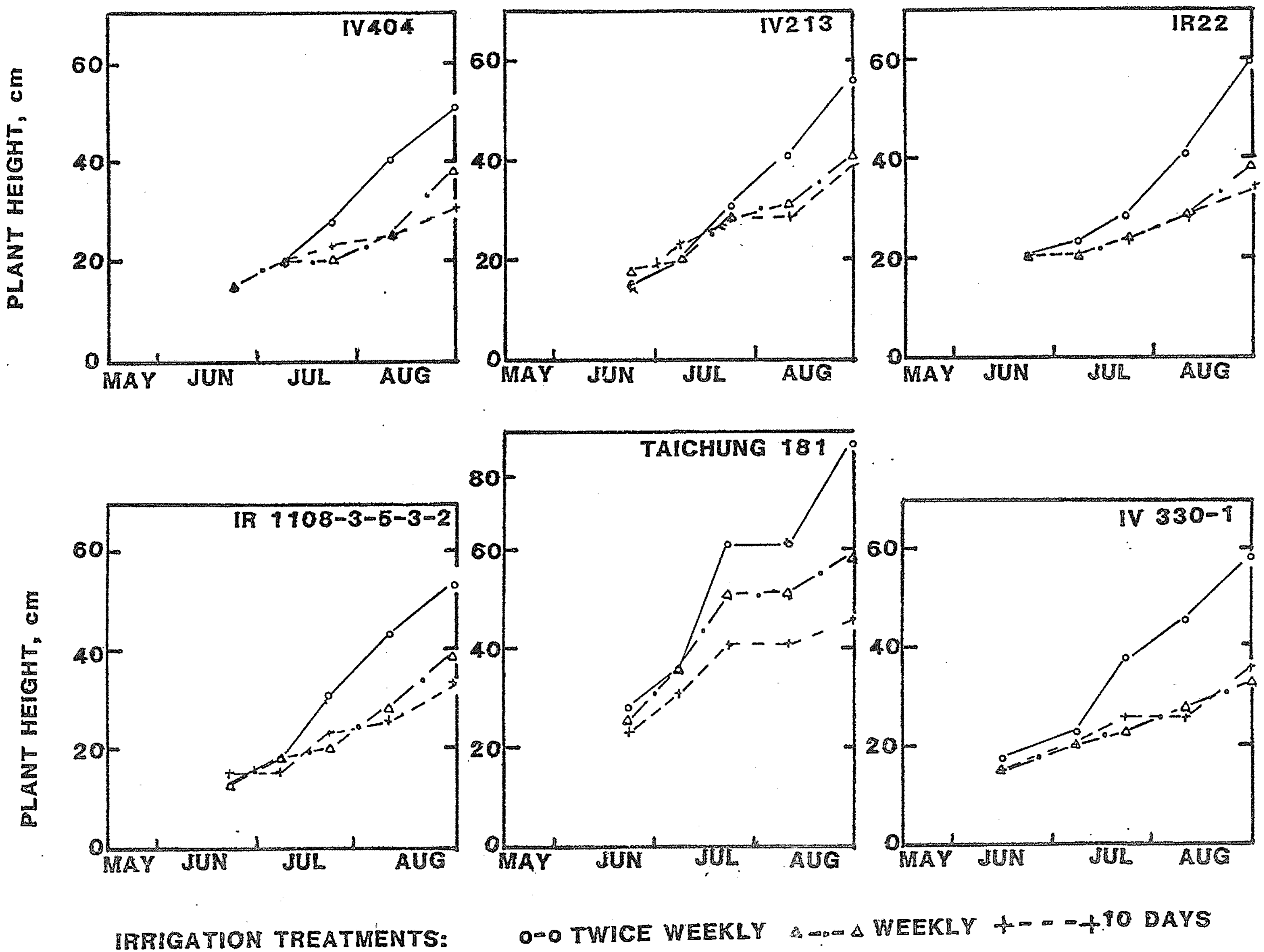

Figure 3. Effects of three irrigation treatments on plant growth for six rice cultivars planted at Yuma, Arizona, on April 29, 1981.

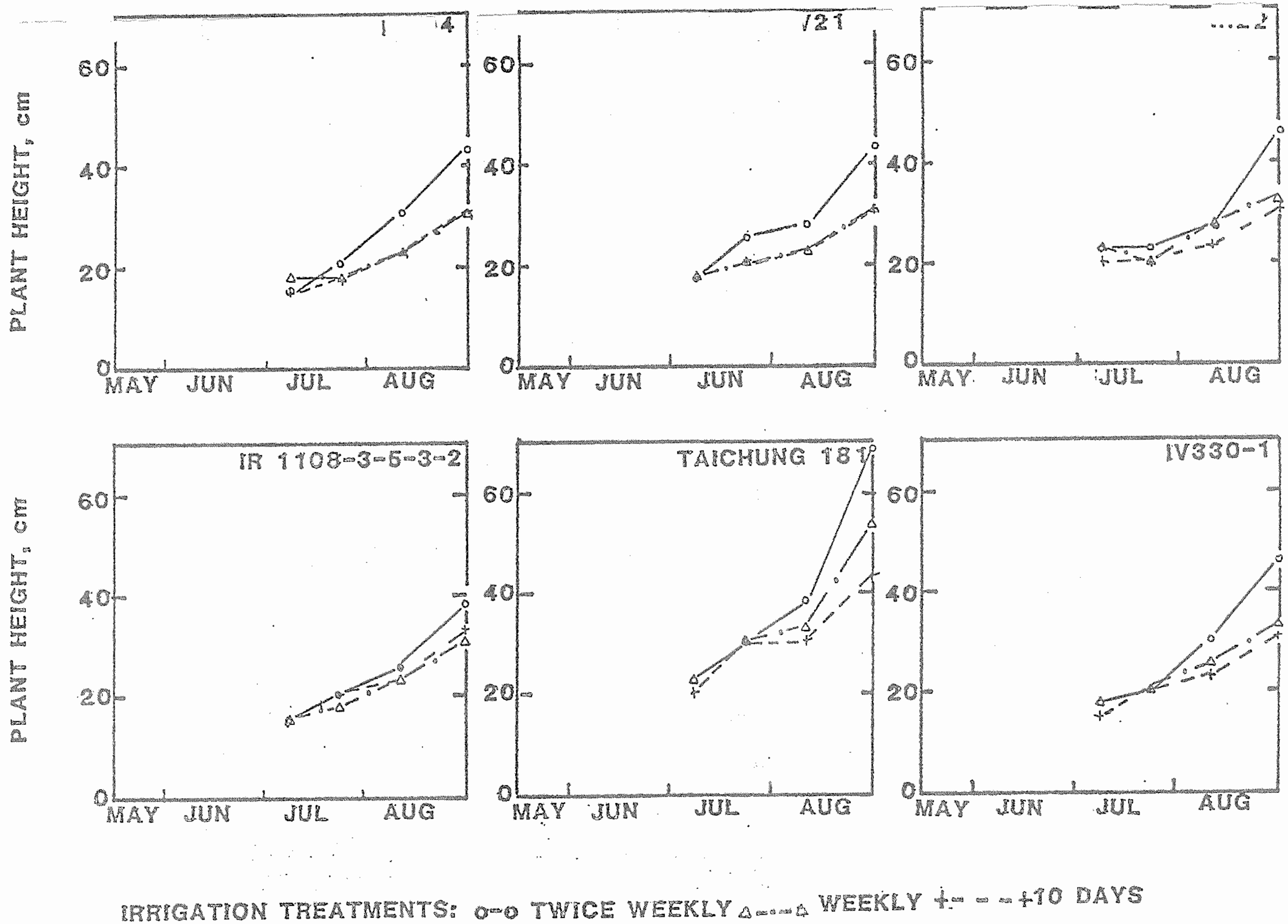

Figure 4. Effects of three irrigation treatments on plant growth for six rice cultivars planted at Yuma, Arizona, on May 27, 1981.

TITLE: IRRIGATION WATER, CULTURAL PRACTICES, AND ENERGY ASPECTS OF CANTALOUPE PRODUCTION IN ARID REGIONS

NRP: 20740 CRIS WORK UNIT: 5510-20740-003

INTRODUCTION:

See Annual Report, 1980.

FIELD PROCEDURES:

The 1981 cropping season consisted of four planting/plant population treatments: (1) conventional bed at the standard population, 25 cm (10 inches) within row and 150 cm (60 inches) between rows; (2) corrugated planting at the standard population, same plant dimensions; (3) corrugated planting at a medium population, 25 cm within row and 75 cm (30 inches) between rows; (4) corrugated planting at a high population, 25 cm within row and 50 cm (20 inches) between rows. Irrigation treatments were based on soil-water depletion in the top 60 cm of soil; (1) irrigated when 65% of the soil moisture was used, and (2) irrigated when 75% of the moisture was used. The eight treatment combinations were replicated five times in a randomized-block design for a total of 40 plots. Each individual plot was 10 m wide x 18.3 m long (33 x 60-ft). The size of corrugations were approximately 6 cm (2.4 inches) high and 20 cm (7.9 inches) wide.

Top Mark cantaloupe seed was planted on April 1 and all plots were irrigated on April 2 with each plot receiving 7.4 cm (2.9 inches) of water. The plots were irrigated twice more to facilitate germination and stand establishment. Each plot received 4.9 cm (1.9 inches) on April 7 and 4.6 cm (1.8 inches) on April 13. Plots were thinned on May 6 and 9.3 cm (3.7 inches) of water was applied to all plots on May 8. The medium treatment then received for the remainder of the growing season 11.1 cm (4.4 inches) on May 22, 8.6 cm (3.4 inches) on June 9 and 25, and 11.1 cm on July 1. The dry treatment was given 10.7 cm (4.2 inches) on May 28, 8.6 cm (3.4 inches) on June 17, and 11.1 cm (4.4 inches) on July 1. A total of 58 cm (22.9 inches) of irrigation water was applied to the medium treatment and 57 cm (22.3 inches) to the dry treatment. All plots received 1.2 cm (0.5 inches) of precipitation during the growing season. Irrigation water was measured through a 10-cm (4-in.) propellor-type water meter.

Fertilizer applications consisted of 168 kg/ha (150 lb/acre) of ammonium phosphate (16-20-0) broadcast over the field before planting, 122 kg/ha (109 lb/acre) of urea (46-0-0) after thinning, and 122 kg/ha of urea after early runners. The last two fertilizer applications for all plots were applied in the irrigation water through an injector pump. Total fertilizer applied was 139 kg/ha (124 lb./acre) of N and 34 kg/ha (30 lb/acre)of P.

Consumptive use was estimated from changes in soil water content at two sites with two locations per site for the medium and dry irrigation treatments with the standard plant population on the corrugated plantings. Soil moisture samples were taken to a depth of 120 cm (4 ft).

Cantaloupe harvest began on July 6 and continued until July 20. Melons were sized, counted, and graded three times a week. Four sizes were determined as 23, 27, 36, or 45, by use of a prescribed sizing template. These sizing numbers are the number of melons that can be packed in a commercial shipping crate (56 x 33 x 33 cm). All melons smaller than 45, rotten, soft, ground spotted, slick, or split, were considered culls.

RESULTS AND DISCUSSION:

The 1981 measured seasonal consumptive use was similar for both the medium and dry irrigation treatments, 36.8 cm (14.5 inches) on the medium, and 35.6 cm (14.0 inches) on the dry, as shown in Figures 1 and 2. The similarity in amounts used by the two treatments is not unreasonable since the medium treatment received only one cm more of irrigation water. The total use was considerably lower than in past years. Temperatures were similar as in past years in the early part of the growing season. However, temperatures became somewhat cooler about the time of peak use and remained cooler throughout the harvesting phase. Daily consumptive use was rather low during this period when normally it is still quite high.

Yields for cantaloupes are summarized in Table 1. The effect of scheduling of irrigations is shown by a 32% increase in marketable crates per hectare for the medium over the dry treatment. This increase is also highly significant in terms of total fruit and numbers of larger fruit harvested. The lower production on the dry treatment as compared to the medium treatment can be attributed primarily to stressing the plants during the peak blossoming period and when fruit was maturing the fastest.

Corrugated plantings produced about 25% more marketable fruit than standard beds on the medium treatment but doubling the plant population increased yield by only 15%. There were essentially no differences on the dry treatment either by planting method or by doubling the population. Tripling the population actually reduced yields on both treatments. Total harvested fruit was about the same but a high percentage of the melons were too small to be marketable. The medium treatment wad 23% more fruit of size 36 and larger, and 33% less culls. Total fruit harvested was nearly the same for both treatments.

SUMMARY AND CONCLUSIONS:

Over the past three growing seasons, spring cantaloupes were produced under medium and dry irrigation treatments using conventional beds with standard plant populations and a nearly flat corrugation treatment with standard, double, and triple populations. Doubling the plant population increased yields from 10 to 18%, while planting on corrugations improved yields by an average of 9%. The highest plant populations tended to decrease yields primarily because fruit did not attain marketable size. Timing of irrigations is a definite factor in maximum yields as noted by the average 25% higher production in the medium treatment as compared to the dry treatment. The development of dead-level corrugated plantings with high populations has the potential for improving irrigation efficiencies and energy requirements.

ERSONNEL:

ale A. Bucks and Orrin F. French (U. S. Water Conservation Laboratory); . D. Pew and W. L. Alexander (University of Arizona, Mesa Experiment Farm).

Table 1. Summary of spring cantaloupe yields (mean of 5 replications), 1981.

Irrigation Treatment	Planting method	Plant population	Marketable crates per hectare	No. fruit per plot 36 & larger	Total No. fruit per plot harvested	Percent culls
Medium	Bed	25,800/ha	836	47	65	12
Medium	Corrugation	25,800/ha	1047	60	80	19
Medium	Corrugation	51,600/ha	1238	67	108	20
Medium	Corrugation	77,400/ha	774	37	98	41
Dry	Bed	25,800/ha	793	43	63	16
Dry	Corrugation	25,800/ha	840	49	73	16
Dry	Corrugation	51,600/ha	747	39	104	45
Dry	Corrugation	77,400/ha	680	31	130	61
			*	**	**	**

* Significant difference at 5% level

** Significant difference at 1% level.

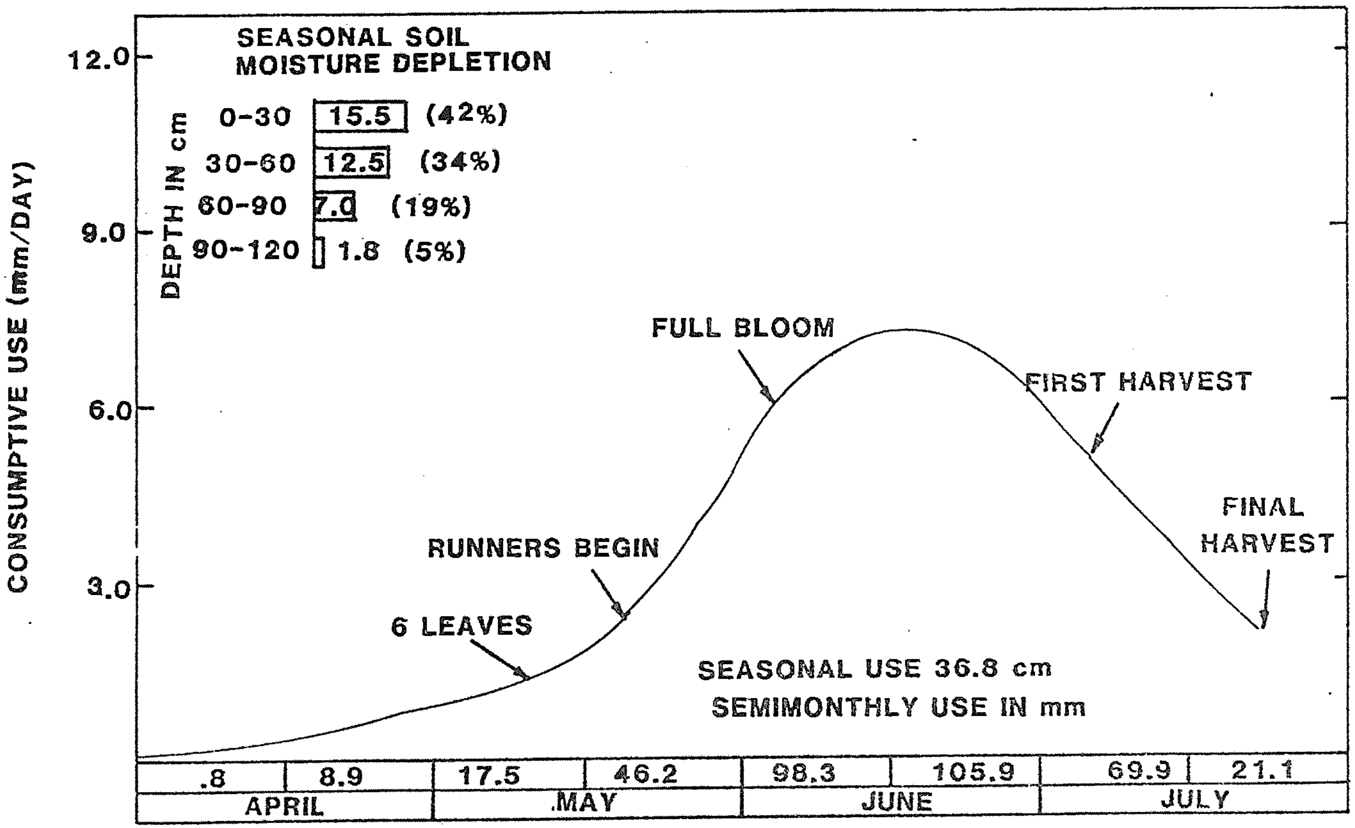

Figure 1. Mean consumptive use curve for a medium irrigation treatment on spring cantaloupes at Mesa, Arizona, 1981.

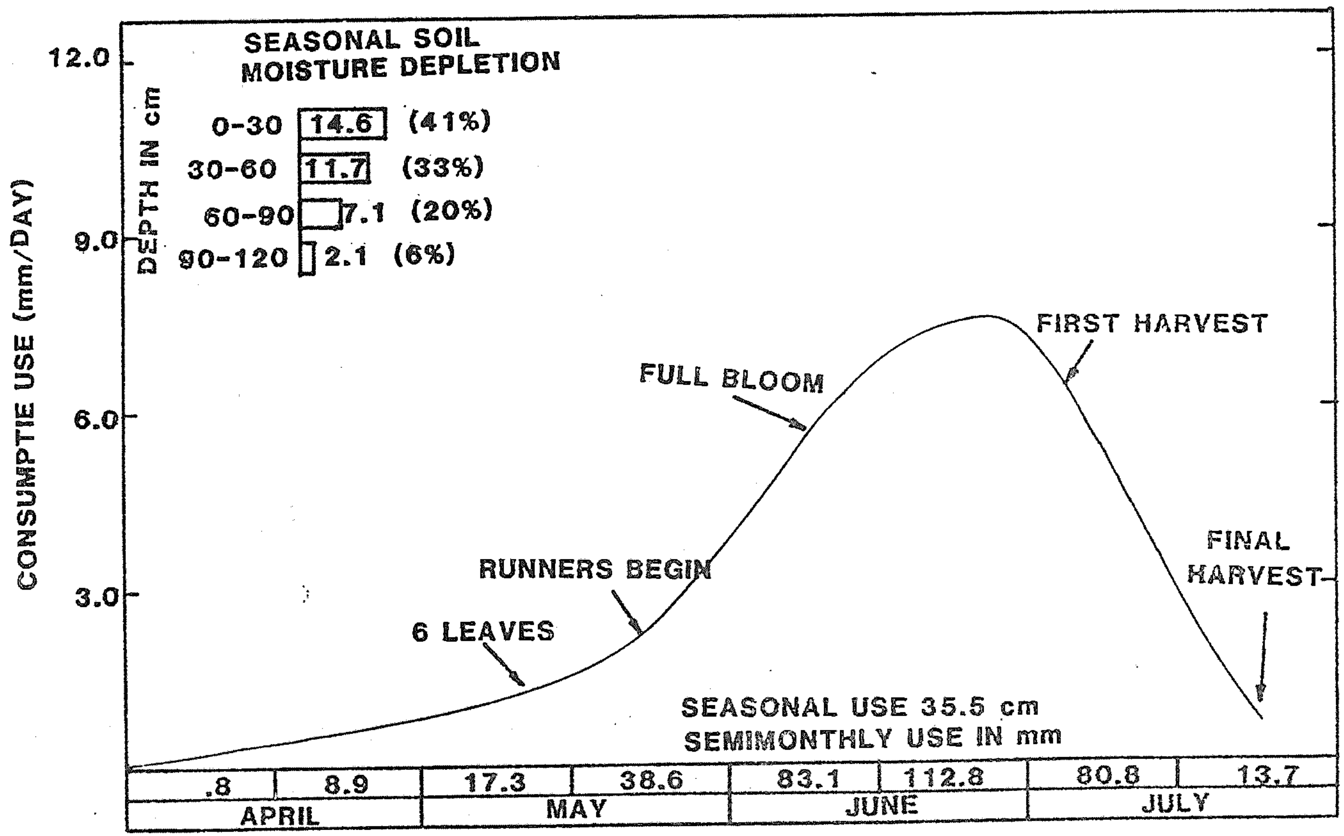

Figure 2. Mean consumptive use curve for a dry irrigation treatment on spring cantaloupe at Mesa, Arizona, 1981.

TITLE: SURFACE IRRIGATION AUTOMATION

NRP: 20740 CRIS WORK UNIT: 5510-20740-004

INTRODUCTION:

Six automated level basin irrigation systems have been installed in the Wellton-Mohawk Irrigation and Drainage District (WMIDD) since 1975, Table 1. All automated sites, although operational by the cooperating farmers, have been used for further research, development, and evaluation purposes. Seven additional automated systems have been designed through 1981, but no specific plans have been made for completion of these systems. All but one of the six automated systems (McElhaney-McDonnell #2) uses time to effect the switching from basin to basin. Early in our work we considered flow fluctuation of water deliveries within an irrigation district to be insignificant. We have found, however, that the fluctuation problem is more widespread than originally thought and in some instances farmers considered time-based control to be unsatisfactory -- Joe Hoffman #1 and Woodhouse. Hence, an expanded research and development program was started in 1980 to get equipment into the field that could be used to adjust the water delivery by automatically compensating for flow fluctuations.

Research and development during 1981 centered around interfacing normally time-based control centers to open channel flow measuring devices to provide volumetric control, with the main emphasis on using pressure transducers and bubblers to detect water depth upstream from a flume. New control centers were designed and constructed for four of the five time-based automated systems (all but McElhaney-McDonnell #1) featuring volumetric control. Gophers destroyed some polyethylene tubing (not originally encased) on the Naquin automated port system during 1980. The system was replumbed and revised during 1981. Both Hoffman automated systems were originally independent of 110 VAC power, but AC power was supplied to the sites during 1981. Control centers were constructed to utilize the new power supply and to accommodate the volumetric control feature once ready for field installation. Specific changes made at the various automated sites will be outlined.

VOLUMETRIC CONTROL:

The basic components required for interfacing with an open channel flow metering device, where flow rate is predictable from a water depth measurement, include a water flow depth detecting technique with output proportional to depth and generally a voltage controlled oscillator (VCO). A power function amplifier (discharge related to flow depth by power function) may be required depending on the capability of the controller used. Volume delivered may be represented by accumulating the flow (integrate) with time or by adjusting the controller delivery time based on flow rate changes from a pre-selected nominal flow. In our work the latter procedure has been developed and features a power function amplifier output being converted to a pulsed output from the VCO. The VCO output (proportional to flow rate) was interfaced with a time based controller, manufactured by RainBird Sprinkler

Mfg. Corp.[1/] More detail of these components were included in the 1980 Annual Research Report and in a paper entitled "Open channel flow sensing for automatic control," presented at the 1981 Winter meeting of the American Society of Agricultural Engineers.

The calibration accuracy for broad-crested weirs and critical flow flumes which the volumetric controls are being interfaced is about ±2 to ±3%. The discharge (q) can be predicted from upstream water depths (h) to within about ±0.5% of actual when a power function ($q = ah^b$) is fitted to the flume calibration data for flow ranges of 300 to 900 L/s. Two percent accuracy translates into a vertical detection requirement of about ±3 mm for the broad-crested-weirs and nearly double that for the critical-flow flumes for flow rates above 300 L/s, Table 2.

We have tried two depth measurement methods -- capacitance and bubbler/pressure transducer. In the capacitance unit, a variable capacitor is formed by a probe and metallic walls of a container or a special ground plate. The probe is one plate of the capacitor, and the walls or ground plate being the other. The material between the two (water) is the dielectric. Capacitance is measured by a bridge circuit excited by a high frequency oscillator. As the water level changes the dielectric constant changes. The capacitance varies linearly with water level. Limitations of the capacitance system are: probe is in contact with the fluid which may eventually result in reduced measurement accuracy -- coating buildup from water, especially when fertilizers are injected during the irrigation; the high frequency oscillator must be located at the capacitor -- many times remote from the control center; and the analog output from the probe is subject to losses associated with distance.

The bubbler unit is one of the oldest and simplest level measuring devices wherein a tube or pipe is placed at the bottom of the water column to be measured (zero of a flume in our case). Air flowing through the tubing causes bubbles to escape through the water. The air pressure at the end of the tube where the air escapes corresponds to the hydraulic head of the water, and can be sensed with a pressure transducer. The pressure transducer can be located remotely from the flow metering device and bubbler (i.e., at the controller if desired). This has the advantage of centrally locating all electronic equipment with only the bubbler contacting the water. The distance between the bubbler and transducer is essentially unlimited if dual tubes are used; one for supplying the bubbler and the other, teed to the first near the bubbler, for sensing the pressure. For short distances, single tubes from the transducer to bubbler can be used since pressure losses will be small. The distance between the transducer and bubbler for the single tube can be increased by increasing the tubing size. Tubes can be very small (2 or 3 mm ID) when dual tubes are used since pressure losses are not a concern. A flow control valve is required to provide about 5-10 bubbles per second at the bubbler.

1/ Trade names and company names are included for the benefit of the reader and imply no indorsement or preferential treatment of the product listed by USDA.

Electronic equipment used to provide a digital signal was commerically available, an important aspect in assembling an automation package in the future. The capacitor system in addition to the probe included: power supply for the high frequency oscillator and output display, high frequency oscillator, exponent converter, and voltage controlled oscillator. The equipment, including the probe, was manufactured by Endress-Hauser, Inc. of Greenwood, IN.

For the bubbler/pressure transducer scheme, the various electronic components included in modular form: pressure transducer bridge excitation and amplifier, exponent module which provides an output proportional to the input raised to a power (exponent b of $q = ah^b$), and a voltage controlled oscillator whose output is proportional to the analog input signal. This equipment was supplied by Action Instruments Co., of San Diego, CA. The pressure transducers were supplied by Foxbore/I.C.T., Inc. of San Jose, CA. The particular transducers selected are intended for a maximum pressure of 635 mm (25-in) of water with a nominal output of 25 mv.

Temperature Sensitivity

Most of the equipment described has a long history of use. The accuracy with which water depth must be detected is greater for our application than for many others. Bubbler's for example, have been used for years to measure the depth to water in wells, but a high degree of accuracy is not required. Furthermore, near constant temperatures can be maintained in many industrial applications. Considering the extreme environmental conditions under which we will use the equipment and the accuracy requirements, a rather extensive testing program was undertaken to evaluate the temperature stability of the equipment. In most cases, some temperature compensation was part of the purchased equipment.

Capacitance System

The capacitance system that was eventually installed on the McElhaney-McDonnell #2 farm, was tested in the laboratory by inserting the probe-stilling well system into a variable head tank. The procedure involved setting the temperature in the control room and once stabilized, a calibration test was conducted. Calibration involved adjusting the depth (head) incrementally and recording the voltage output from the capacitor, the voltage from the exponent convertor, and frequency from the voltage controlled oscillator. The head-discharge relationship was then developed using a power function curve-fit procedure where discharge q, was represented by either voltage or frequency. The repeatability of calibration runs at a fixed temperature was excellent. However, the capacitor system underestimated flow rate as air temperature increased. Flow rate error decreased linearly over the temperature ranges tested, Fig. 1. The curves shown were for h=610 mm. As h decreased, the error also decreased. When the power supply for the high frequency oscillator, exponent convertor, and voltage controlled oscillator were isolated from the probe and high frequency oscillator assembly, and maintained at a constant temperature, the error was reduced by about half (slope of curve = -.12%/°C vs -0.23%/°C), Fig. 1. If the temperature of the equipment separated from the probe assembly could be controlled at some constant value this reduced error would result. In the field where we have been using the equipment, temperature is not controlled, hence the error we might expect may be estimated from the steeper line of Fig. 1.

During the period when most of the irrigating is done in southwestern Arizona (May through October) the average temperature is about 30°C. Adjusting the electronic equipment for zero error at nominal flow when the temperature is about 30°C will minimize the error in flow rate detection for the majority of irrigations. If such adjustments were made, a 2% error in flow rate due to temperature would be maintained over a temperature range of about 21 to 39°C while the temperature range would be about 17 to 43°C for a 3% error, Fig. 1. If the temperature were controlled, for all equipment separated from the probe, 2% error would be maintained over a probe temperature range of about 13 to 47°C.

Bubbler/Pressure Transducer System

The bubbler/pressure transducer system was extensively tested in the laboratory. The temperature of the room in which the tests were conducted could be controlled for temperatures ranging between 5 to 55°C. Stability of the pressure transducers, bridge excitation and amplifier module, and exponent module were all evaluated with respect to air temperature changes. Stability of both modules was excellent, being about 0.015% of span per °C for the bridge output and about 0.0065% for the exponent module. Both were well within the manufacturers' specification.

For test purposes, a constant head (pressure) was applied to the transducers. A bubbler system was used to provide the constant head. The air temperature in the control room was then cycled and the output from the transducers was monitored as the temperature changed.

The transducers were unstable with temperature change, Table 3, and the degree of instability (temperature coefficient) was different for each. Transducer output varied by as much as 3.10 mv to as little as 0.70 mv, with a temperature change of 5 to 55°C. In three of the four cases the output decreased as temperature increased. The millivolt output can be converted to an equivalent water depth (h,mm) by multiplying by 32.9. Upon examining these values in Table 3, the error in measuring h varied from ±11.5 to ±51 mm, which translates to flow rate errors of ±7 to ±30% at a flow depth of 300 mm. As noted earlier, the head detection accuracy should approach ±3 mm for the b-c-w to maintain ±2% error in measuring flow rate.

Accuracy requirements can be met with the pressure transducers by maintaining a near constant transducer temperature. We decided to evaluate the transducer stability when the temperature was held constant above the maximum ambient expected. Ovens are commercially available for this application and were supplied by Ovenaire, Inc., of Charlottesville, VA. Temperature control is within ±2°C from the customer specified temperature. The specific oven we used was rated at 79°C and operated on 24 vdc (other voltages available). The transducer that was most sensitive to temperature (1 in Table 3) was tested with the oven, the results of which are shown in Table 3. The transducer output varied by 0.20 mv over the 50°C temperature range, which translates to an apparent head detection accuracy of ±3.3 mm or ±1.9% flow rate error. All other transducers would be more accurate. To achieve this control the oven and transducer assembly was insulated from the surrounding air by using 6-mm-thick, closed-cell foam rubber sheeting. We plan to use the pressure transducer systems equipped with ovens to implement volumetric control on four of the time based automated systems in the Wellton-Mohawk Irrigation and Drainage District during 1982.

Field Use-Capacitance System

The capacitance system has been used on the McElaney-McDonnell #2 automated system since October 1980. The system has been monitored several times since installation to evaluate how accurately the required volume of water is being applied. The system calibration has not been changed since installed. On 9 September 1981, the calibration of the system was checked and volume of water applied during an irrigation was measured on six basins.

The exponent for the power function relating head (h) to voltage from the exponent convertor (discharge) was 2.146, compared to 2.148 when installed in 1980. Total hours set on the controller for the six basins was 7.7, which represents an application depth of 10.2 cm (net) with a nominal flow of 690 L/s. The flow rate averaged about 610 L/s. The time adjustment to represent the correct volume of water would be 690/610 x 7.7 or 8.7 h. Water was applied for 527 minutes of 8.78 h.

AUTOMATED SYSTEM CHANGES:

Preparation was made during 1981 to convert four of the time-based automated systems to volumetric control. In some instances this involved additional electrical wire and air supply tubing installation while in others only control center changes were required. Control centers were designed and constructed for the additional four sets patterned after the control center used on the first volumetric system at McElhaney-McDonnell #2. These control centers feature:

1. 12-station microprocessor based controller/timers manufactured by RainBird Sprinkler Mfg. Corp., and previously described water depth sensor and interface equipment.

2. Functional requirements of checkgate signaling, water rundown, and in some instances safety overflow were developed and described for the McElhaney-McDonnell #2 in the 1980 Annual Research Report. The logic was then designed and built to provide the necessary functions using electro-mechanical relays. Random sequencing was provided by matrix boards.

Originally plans had been made to install the volumetric equipment during 1981 but unforeseen problems with the pressure transducer bridge excitation and amplifier module and excessive temperature sensitivity of the transducers themselves (described earlier) prevented field installation during 1981.

Module repair and transducer testing has been completed. The controller interface used to adjust the time base of the controller proportional to flow rate changes was originally designed and built using a hard wire circuit board and conventional control logic. We redesigned the system during 1981 to use a microprocessor based control system in conjunction with a printed circuit board. The printed circuit boards must yet be constructed to complete the entire system.

Woodhouse System

The original, pneumatic operated, control center was removed and replaced with a new control center. Gate signaling is still done pneumatically by converting the 26.5 vac controller output signal to a pneumatic signal by a relay and solenoid operated three-way valve scheme. No changes were made in the installation outside the control center. Checkgate signaling, rundown, and safety overflow were part of the control center. Failure of the pressure transducer bridge excitation and amplifier modules was first discovered while installing the equipment on the Woodhouse system. The amplifier failed during installation on 19 August 1981, when air temperatures in the control shed reached 53°C. The control system was used on a time basis only during the fall of 1981.

Naquin System

The automated system was replumbed and rewired, and a new control center was installed during 1981. Replumbing and rewiring were patterned after the McElhaney-McDonnell #2 system in which a pair of 14 ga. wires were daisy-chained to all 24 vdc solenoid operated valves used to control the lift-gates or ports. Switching the 24 vdc power to specific gates or ports was accomplished by using a 24 vac relay, signaled over 22-ga. wire. The dc power supply output is adjustable and automatically adjusts voltage output via remote sensing features. Port and checkgate controls were housed in instrument cabinets (subcenters) attached to the checkgates. All electrical wire and air tubing was brought to these locations, encased in 1½ in. PVC pipe for rodent protection. Air from the subcenters to ports along any basin was carried in ½ in. unprotected PVC pipe.

The features of overflow selection, manual override, and signal interrupt were included at the subcenters. A subcenter in which two basins would be affected by a single checkgate is shown as Fig. 2. This configuration provides normally closed basin ports and a normally open checkgate. Overflow signals from float controlled microswitches were 24 vdc. A single air tube (3/8-in. dia) was installed for the bubbler system, and was encased along with the other tubing and wire.

Installation time for the new system was 165 man-hours. Crew size ranged from 2 to 5, depending on the requirements. Items completed included about 4,2[illegible] ft of 1-ft deep trench — constructed with a riding trencher; 2160 ft of encasing constructed at a rate of 240 ft/man-hr; port-air supply lines made by gluing 20 ft lengths of ½ in. PVC; air connections to ports made at rate [illegible] minutes/port; control center installation, including all air and electrical connections at the control center and subcenters; and system testing for air leaks and electrical integrity.

Several irrigations were completed during the fall of 1981 using the time based controller. In the original design of the Naquin system in 1976, port closure was quicker than port opening which resulted in water buildup in the canal and overflow operation during standard switching from basin to basin. In the present design, in which relatively large ported valves were used at the subcenters, depressurization (venting) of the air bellows is rapid enough to allow switching from basin to basin without water level buildup (no delay in opening vs. closing), Fig. 3.

McElhaney-McDonnell #1

Minor maintenance of this 1977 installed system included replacing a few exposed polyethylene tubes that either broke due to UV degradation or in a few cases were chewed (coyote suspected), lubrication of cylinder rods, and adjustment of one overflow. A plastic tube was installed from the control center to the flume -- about 650 ft, to provide a bubbler for future conversion of the time-based system to volumetric control.

Hoffman Automated Systems

Maintenance of batteries (rechargeable) and air bottles (replacement) and excessive flow fluctuation of the Joe Hoffman #1 system proved to be serious limitations in proper usage of the Hoffman systems. AC power has been supplied to the systems, some replumbing and rewiring was completed to accommodate the relocation of two gate turnouts, control centers were designed and built to incorporate volumetric control using bubblers, a new broad-crested-weir was installed on the Joe Hoffman #1 system, and air tubes to the bubblers at the flumes were installed. Control centers will be installed and available for use in 1982. Neither system was used during 1981.

McElhaney-McDonnell #2

The automated system, installed in 1980, was used throughout 1981. The functional requirements of safety overflow, checkgate signaling, and rundown were originally built using a microprocessor based system. This system was replaced with electro-mechanical relay logic to facilitate maintenance. Details of this system were included in the 1980 Annual Research Report. This automated system was featured at a level-basin irrigation and automation field day and tour held on 26 February 1981, sponsored by the University of Arizona. Two popular articles resulted: "Surface irrigation goes automatic," 1981. Western Hay and Grain Growers. 10(4):4-5; and "Automatic flood gates ready for commercial effort." 1981. Irrigation Age 15(9):18-19.

Three transformers providing the station output signals from the commercial controller failed during 1981. Failure apparently is caused by an undetermined overload (excess of 2 amps) -- normal output requirements are about 50-100 ma. A transformer with a higher current rating has been installed, and no failures have occurred since. The cause of the problem will hopefully be found during 1982.

Rodents destroyed the insulation of one of the buried electrical wires used to power the control center, which lead to failure when corroded later. The electrical power supply will be replaced during 1982.

The commercially purchased float-microswitch system used to signal excessive water depth in the canals (overflow) was modified to provide a more positive action of the microswitch. This involved a larger float, added weight to the float, and adjusting the holding bracket to accommodate the larger float. All were modified on the McElhaney-McDonnell #2 system in 1981. The modified versions will be added to the Naquin and Hoffman systems in 1982.

SUMMARY AND CONCLUSIONS:

Six automated level basin irrigation systems have been installed in the Wellton-Mohawk Irrigation and Drainage District since 1975. One new system was designed during 1981. Six others have been designed previously but no specific plans have been made for completion of these systems.

Flow rate fluctuation during an irrigation can cause appreciable error in volume of water applied if time based deliveries are used. These fluctuations appear to be a more serious problem than originally thought. To compound the problem the flow rate received may vary appreciably from that expected, hence predetermined time settings may not be accurate and would negate one of the important advantages of automation — convenience. Hence, an expanded research and development program was started in 1980 to get equipment in the field to provide volumetric delivery by compensating, automatically, for flow changes either during an irrigation or from irrigation to irrigation.

Research and development during 1981 centered around interfacing normally time-based controllers to open channel flow sensors to provide time adjustments to compensate for flow changes from some predetermined nominal.

Bubbler/pressure transducers and capacitance methods of water depth detection have been evaluated. One capacitance system has been successfully used on farm since October 1980. The system calibration has not changed appreciably since installed, and operation and function of the equipment appears to be satisfactory.

The bubbler/pressure transducer system was extensively tested in the laboratory especially for temperature stability. The transducers studied were temperature sensitive but if the temperature of the transducers were elevated above ambient and held near constant the accuracy was near ±2% (flow rate) over a 50°C temperature range. We plan to use the pressure transducer systems equipped with ovens to implement volumetric control on four of the time based automated systems.

During 1980, gophers damaged the polyethylene tubes on the original Naquin automated system. The system was replumbed and rewired. The new system features electrical signaling and volumetric control. This system and the Woodhouse automated field were operational on a time-base only, during the fall of 1981, using new control centers patterned after the first volumetric control center. They will operate volumetrically when all interface equipment is available.

Maintenance of batteries and air bottles, to provide independence from 110 vac power, proved to be serious limitations in proper usage of the Hoffman systems. AC power was supplied to the fields and some additional electrical rewiring and tubing replumbing was necessary to accommodate the change. New control centers, with volumetric control, will be installed during 1982. The wire and tubing on the Hoffman Enterprises #1 system, embedded in the concrete at the time the ditch was lined, was still functional during 1981.

PERSONNEL:

Allen R. Dedrick

Table 1. Automated irrigation systems in Wellton-Mohawk Irrigation and Drainage District.

Year Installed	Owner/Operator	Acres	Number of Basins	Number of Checkgates	Number of Overflows
1975[1/]	Woodhouse	65	8	1	2
	Naquin[2/]	70	8	3	3
1977[3/]	McElhaney & McDonnell #1	64	23	2	4
1979[3/]	Joe Hoffman #1	110	8	2	3
	Hoffman Enterprises #1	80	12	1	2
1980[3/]	McElhaney & McDonnell #2	76	9	4	5
	Total	465	68	13	19

1/ Research/Demonstration at USDA-ARS request.

2/ Automated ports — all others were lift-gates.

3/ Operational systems, cost shared by SCS.

Table 2. Head detection accuracy required with broad-cresed weirs and critical-flow flumes to maintain 2% accuracy at various flow rates.

Flume Type	Flow rate, L/s 300	600	900
	(mm)	(mm)	(mm)
Broad-crested weir	±2.7	±4.0	±5.1
Critical-flow flume	±3.8	±5.3	±6.4

Table 3. Temperature sensitivity evaluation of four pressure transducers (same model). Transducer output for constant pressure from a bubbler system.

Transducer Number	Transducer Output 5°C	55°C	ΔMV	Apparent Δh[1/]	Average Apparent Flow Rate Variation[2/]	
	(mv)	(mv)		(mm)	(L/s)	(%)
1	15.95	12.85	3.10	102 (±51)	±135	±30
2	16.00	14.30	2.70	89 (±44.5)	±117	±26
3	11.90	9.70	2.20	72 (±36)	± 94	±21
4	9.85	10.55	-0.70	23 (±11.5)	± 30	± 7
1 w/oven	13.15	12.95	0.20	6.6 (±3.3)	± 8.7	± 1.9

1/ Δh ~ 32.9 mv

2/ Variation calculated from nominal flow when h = 300 mm. $q = 0.021\ h^{1.75}$ where h is mm and q is L/s.

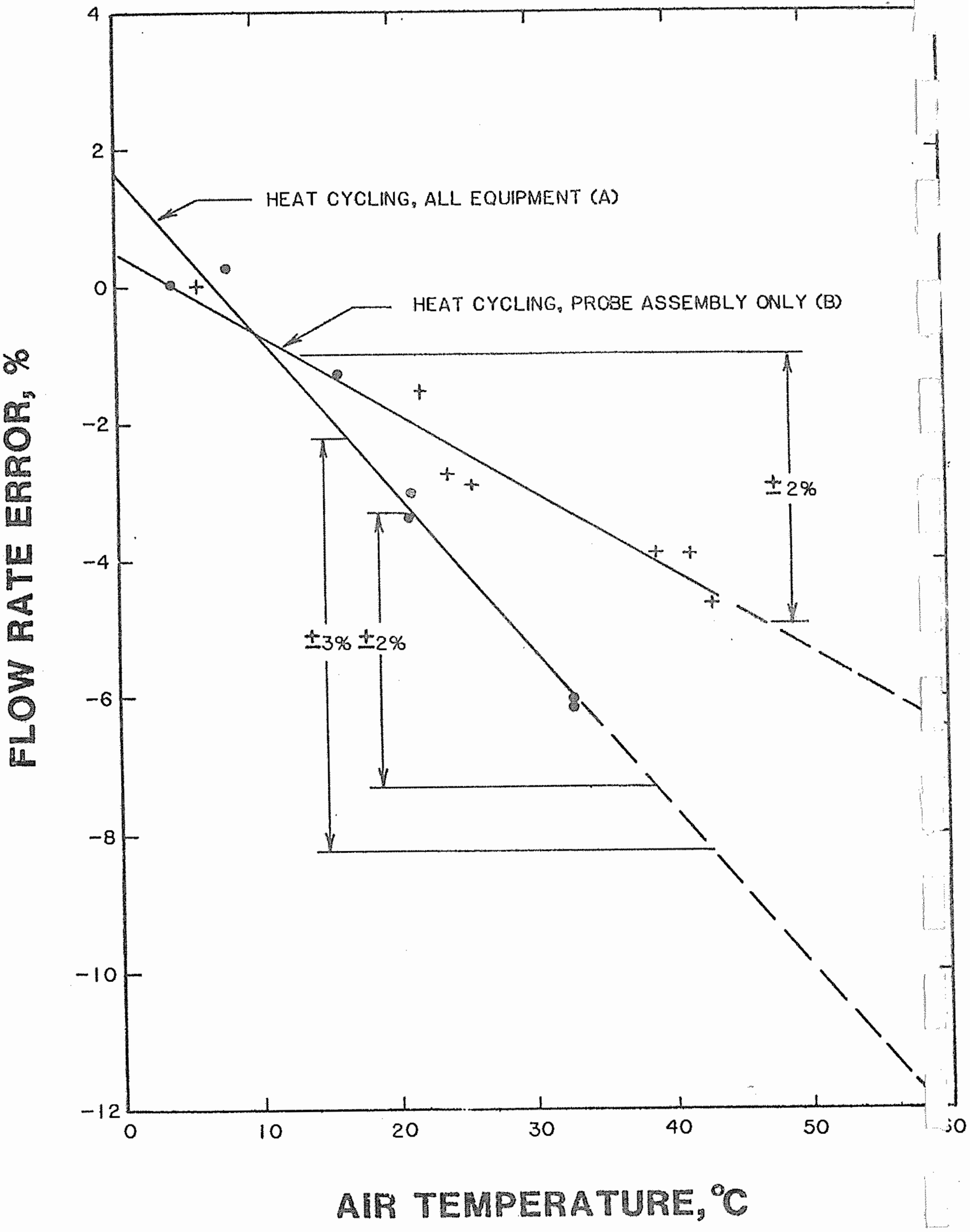

Fig. 1. Influence of temperature on flow rate measured with capacitance system. The effect of temperature cycling on all equipment compared to the capacitance probe assembly only is illustrated by the difference in slope of (A) and (B). The brackets represent the error if the equipment were adjusted to zero error at 30°C.

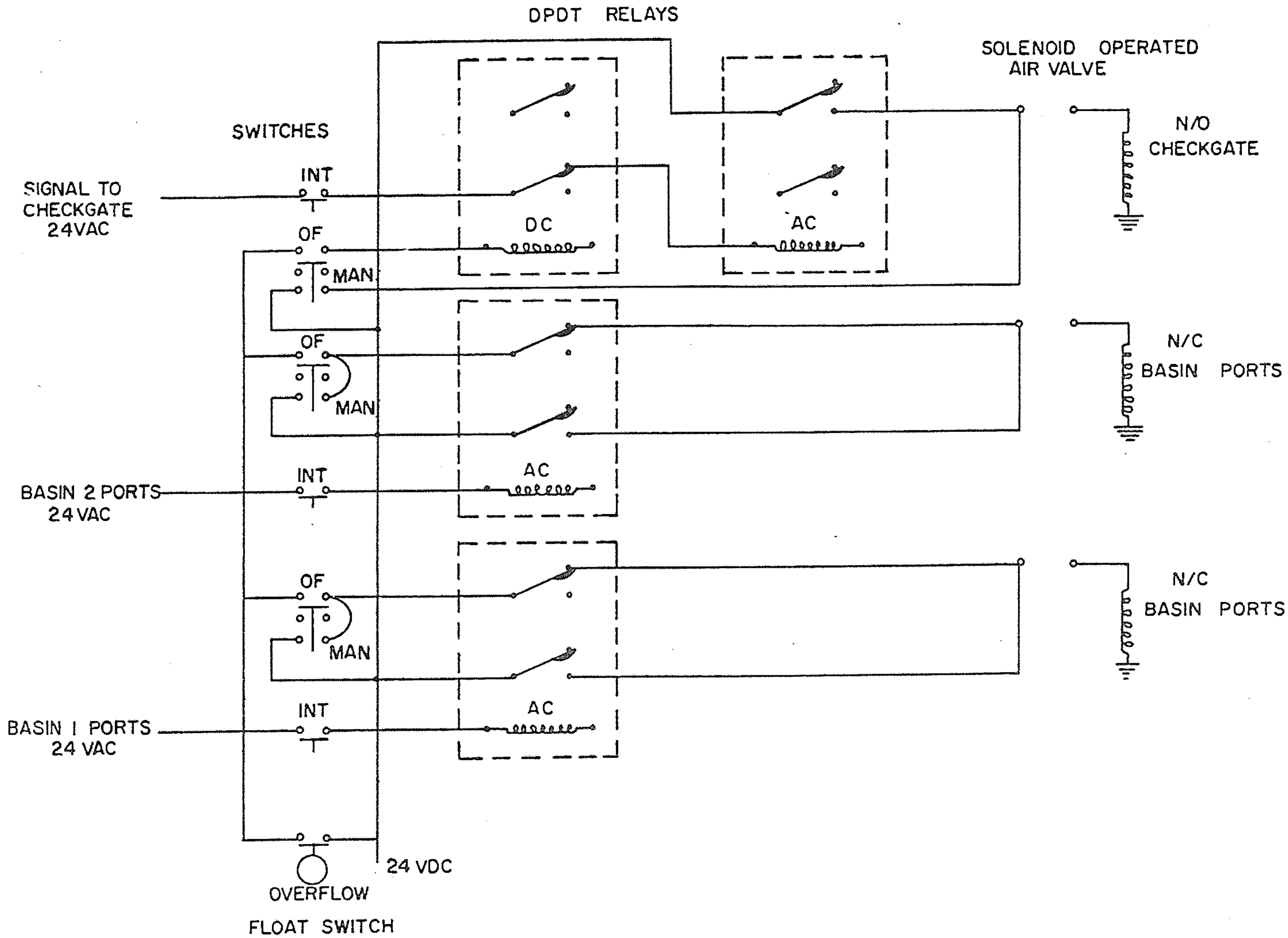

Fig. 2. Diagram of switches, relays, and solenoid operated air valves located at each subcenter on the Naquin automated system. Switch coding is interrupt (INT), overflow selection (OF) and manual override (MAN). Relay voltage is indicated near coil, and gate normal mode is shown at the air valve.

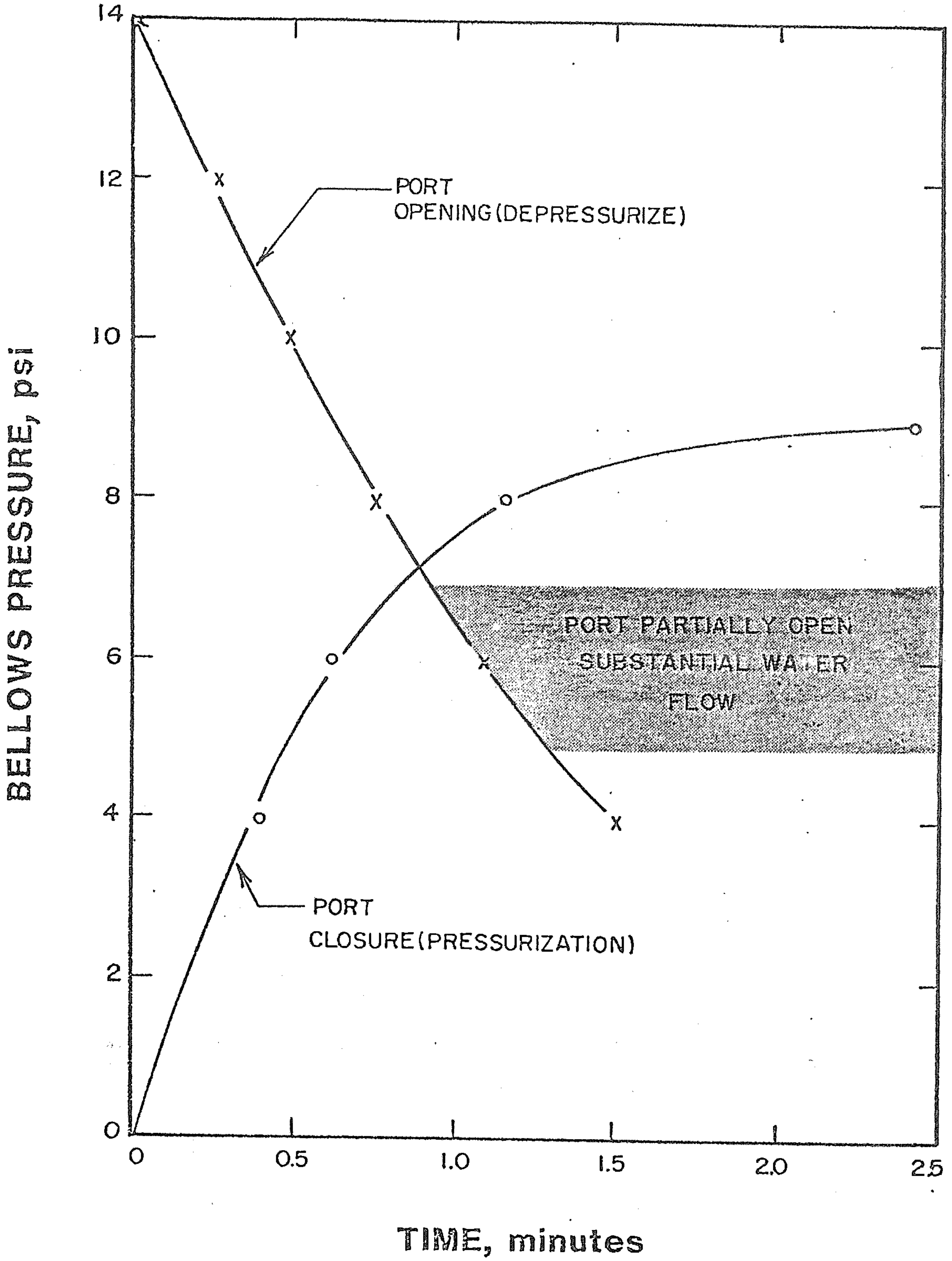

Fig. 3. Bellows (port) pressure on the Naquin automated system related to time after 4-way solenoid operated air valve switched. Me⁻surements were taken on Basin 3, Port 6 (nearest Checkgate 2. Shaded zone indicates when a substantial amount of water is flowing from the port.

TITLE: A COMPUTER MODEL OF GUAYULE

NRP: 20740 CRIS WORK UNIT: 5510-20740-012

INTRODUCTION

The need to secure a domestic source of natural rubber has led to a renewed interest in developing guayule into a commercial crop. The obstacles in the path of domesticating a wild plant are many, but the opportunities for making dramatic improvements in productivity and water use efficiency make the effort exciting.

During the Emergency Rubber Project of World War II, a start was made in selection and development of improved varieties, and in development of appropriate cultural practices. Relatively little was done to study the basic physiology of the guayule plant. Growing a crop of guayule involves many physiological processes including photosynthesis, respiration, growth, transpiration, and rubber synthesis. The integral of these and other processes over a season results in the final yield. Both positive and negative responses to weather and climate changes occur, and the interdependence and feedback within the total physiological system are very complex. Therefore, it is not surprising that field experiments conducted in different locations or in different years in the same location often give very different results. At the present time it is impossible to predict the yield or water use of guayule with any certainty.

Numerous new experiments have been initiated at several locations that can be expected to last several years. Each location and crop life cycle will be conducted under its own set of climatic conditions. One way that the results of these various experiments can be extrapolated to new conditions is to use their results to synthesize a computer model which simulates the various physiological processes. Such a model is based on mathematical relationships that describe the effects of weather and soil variables on the various processes. Once the relationships are known, the weather can be varied from run to run, and the suitability of different locations for guayule production can be predicted. The effects of various management practices such irrigation schedules can also be tested. The relative importance of the various factors affecting production and water use can be studied. Equally important, The process of formulating the model also reveals where important gaps exist in our knowledge about guayule and serves as guide for planning new field or laboratory experiments.

Some of the mathematical relationships can be obtained from existing theory and from data already existing from past guayule experiments. Some are not yet available, and need to be obtained from current and future work. Indeed the model provides a framework from combining the results of many past and future field and laboratory experiments. In this paper I shall present the initial physical framework for such a physiological model.

NOTATION

B	Soil conduction transfer function ($W/m^2 \cdot C$ or dimensionless)
C	Volumetric heat capacity of air (1210 $J/m^3 \cdot C$)
E	Evaporation rate ($kg/m^2 \cdot s$)
F	Angle factor for thermal radiation exchange
G	Soil heat flux (W/m^2)
H	Sensible heat rate (W/m^2)
I	Total number of soil layers
J	Total number of soil columns
K	Hydraulic conductivity (m/s)
L	Leaf area index
M	Molecular weight (kg/mole)
P	Barometric pressure (kPa) or photosynthesis ($kg/m^2 \cdot S$)
R	Thermal radiation (W/m^2)
S	Solar radiation (W/m^2)
T	Temperature (C)
V	Shortening variables defined by Equations 57-58
Y	Shortening variables defined by Equations 31-34
a	Elements of matrix
b	Coefficients for stomatal resistance or soil moisture characteristics
c	Elements of column matrix
e	Vapor pressure (kPa)
g	Acceleration of gravity (9.80 m/s^2)
h	Transfer coefficient (m/s)
k	von Karmann constant
p	Perimeter of vegetation row = 2(w+y) (m)
r	Resistance (s/m)
s	Row spacing (m)
t	Time (seconds)
u	Wind speed (m/s)
w	Row width (m)
x	Horizontal distance from center of origin row (positive to right)
y	Row height (m)
z	Soil depth (positive downward) (m) or cloud altitude or height of windspeed measurement (positive upward)
α	Albedo (or reflectance for solar radiation)
β	Angles in Fig. 4 (radians)
δ	Slope with respect to temperature
Σ	Emittance
Θ	Volumetric soil moisture content (m^3/m^3)
λ	Latent heat of evaporation (2.45×10^6 J/kg)
μ	Vapor pressure to humidity conversion factor = 7.39×10^{-3} $kg/kPa \cdot m^3$
π	3.1416
ρ	Density
σ	Stephen-Boltzmann constant (5.67×10^{-8} Wm^{-2} K^{-4})
τ	Transmittance
ϕ	Plant stomatal response function for water stress
ψ	Soil moisture potential (J/kg)
Δ ( )	Increment of ( )

Subscripts

I	Largest i
J	Largest j
a	Air
c	Constant ratio
g	Soil
i	Index for depth or clouds
j	Index for horizontal spacing
k	Index for first exposed soil segment
ℓ	Index for last exposed soil segment before shade of next row
m	Matric , index for thermal response factors
n	Net
o	Roughness
s	Saturated
v	Vegetation
w	Water
z	Vertical or gravitational
8	8-14 μm band

SUPERSCRIPTS

*	Air saturation
o	"old" from previous iteration

OVERALL MODEL DESCRIPTION

Several simulation models have previously been developed for various crops including wheat, soybeans, alfalfa, corn, sorghum, cotton, and others. The authors have had a variety of objectives, and the models vary considerably in complexity. Various concepts of some of these models have been adapted for this guayule model.

A conceptual view of a guayule crop is illustrated in Figure 1. The crop is imagined to be planted in rows, and Figure 1 shows a cross-section through two of them. The arrows represent fluxes of energy with the direction of the arrows taken as positive. The climate variables include the fluxes of solar and thermal radiation, S_a and R_a; air temperature, T_a; air vapor pressure, e_a; windspeed, u_a; and rainfall. The upward arrows represent fluxes of thermal radiation, R, sensible heat, H, and latent heat, λE, from the vegetation and soil. The grid in the soil is used for numerically storing varing amounts of soil moisture which in turn affects the water stress experienced by the guayule plants and alters the transpiration rate. By balancing all of the energy fluxes, equations will be derived and solved for the vegetation temperature, T_v. Once T_v has been obtained the radiant, sensible, and latent heat fluxes can be calculated, and of equal importance, this temperature can then be used in other equations which simulate the temperature regulation of various physiological processes. Knowing the rates of latent heat transfer means that the rates at which evaporation and transpiration are depleting soil moisture are also known. Then in turn, a soil moisture balance can be used to regulate these water loss rates.

Figure 2 shows the initial overall flow diagram for organizing the guayule model. As is standard, the program will begin by initializing those parameters which characterize the soil and plants and which will remain constant for the particular simulation run. The moisture content in each individual soil segment is also initialized. Then note that there is an hourly and a daily loop. Within the hourly loop, the program reads hourly weather data, and then solar and other non-iterative variables are computed. Next, within an inner iteration loop the vegetation, T_v, and soil surface, T_{gj}, temperatures are computed from the solution to the energy balance equations.

After the plant and soil temperatures are known, the fluxes of energy and water are computed. Then the photosynthetic rate can be computed from the transpiration rate or alternatively from the solar radiation and plant water potential. Data obtained in the future will have to be used to determine the appropriate method. As the hours pass, the rates of photosynthesis, transpiration, and evaporation are integrated with time through the day, so that daily total photosynthate production and water loss are known. Then Figure 2 indicates that daily rubber, biomass, and resin production and growth are computed. As yet, the needed mathematical expressions to describe these all-important physiological processes are unknown, but it is anticipated that future work will provide such equations. For now, Figure 2 shows where they will fit into the model.

Next Figure 2 shows the redistribution of soil moisture. New soil moisture contents can be computed using moisture flow equations to account for movement from one finite element to another (Lambert et al., 1976). Transpired water that has been extracted by roots will be subtrated from the appropriate elements. Similarly, rainfall or irrigation water will be applied to the surface and allowed to fill each layer to field capacity before spilling down to the next lower layer.

The outer loop shown in Figure 2 is labeled hourly, but if future data shows that the "growth" or moisture redistribution needs to occur at another rate than daily, the cycling pattern can be changed.

Finally, at the end of each of the daily loops shown in Figure 2, a test is made as to whether to end the program and "harvest" the guayule. Total crop yields, water consumption, and water use efficiency can then be summarized and printed (or plotted), to complete a simulation run.

SOLVING FOR VEGETATION AND SOIL SURFACE TEMPERATURES

Energy Balance Equations

Referring to Figure 1, a balance of energy fluxes can be written on the vegetation (guayule).

$$S_v + R_{vn} - H_v - \lambda E_v = 0 \qquad (1)$$

Similarly, an energy balance can be written on each jth segment of the soil surface.

$$S_{gj} + R_{gnj} - H_{gj} - \lambda E_{gj} - G_j = 0 \qquad (2)$$

The individual fluxes in Equations 1 and 2 can all be written out in more detail relating them to known weather, soil, and plant parameters and to unknown vegetation and soil surface temperatures. Later, the energy balance equations will be solved to obtain these temperatures.

Solar Radiation

As a first approximation, the solar radiation absorbed by the vegetation, S_v, can be computed from

$$S_v = S_a\ (1 - \alpha_v)\ [w + (y/2)]/s \qquad (3)$$

where S_a is the flux of downcoming solar radiation and α_v is the albedo of the vegetation. The w and y are the width and height of the rows and s is the row spacing, as illustrated in Figure 3. Equation 3 contains the assumption the radiation is absorbed by the top of the row plus the upper half of one of the sides of the row.

The absorption of solar radiation on the jth soil surface segment can be computed from

$$S_{gj} = 0 \qquad \text{all } j \text{ if } [w + (y/2)] \geq s \qquad (4a)$$

$$S_{gj} = 0 \qquad \text{if } x_j \leq w/2 \quad \text{or} \quad \text{if } x_j \geq s - w/2 \qquad (4b)$$

$$S_{gj} = S_a\ (1 - \alpha_{gj}) \left[\frac{s - [w + (y/2)]}{s} \right] \left[\frac{\Delta x}{x_k - x_\ell} \right] \text{ if } w/2 < x_j < s - w/2 \qquad (4c)$$

where x_k is the segment with the smallest subscript that is greater than $s - w/2$ and x_ℓ is the segment with the largest subscript that is less than $w/2$. Equation 4a is the condition of a complete closed canopy and all of the solar radiation is absorbed by the vegetation. Equation 4b is for those segments which are shaded under the right side of the left row in Figure 3 or by the left side of the right row. Equation 4c proportions all radiation not absorbed by the vegetation equally among the soil segments that are unshaded and between the rows.

The albedo, α_{gj}, varies with the water content, as found by Idso et al. (1975). This variation can be simulated by

$$\alpha_{gj} = \alpha_{gMax} \quad \text{if } \theta_{1j} \leq \theta_{dry} \tag{5a}$$

$$\alpha_{gj} = \alpha_{gMin} \quad \text{if } \theta_{1j} \geq \theta_{wet} \tag{5b}$$

$$\alpha_{gj} = \alpha_{gMin} + \frac{(\theta_{1j} - \theta_{dry})(\alpha_{gMax} - \alpha_{gMin})}{(\theta_{wet} - \theta_{dry})} \tag{5c}$$

where α_{gMax} is the maximum albedo which is characteristic of moisture contents less than θ_{dry}. Similarly, α_{gMin} is the minimum albedo characteristic of moisture contents greater than θ_{wet}. Equation 5c provides a linear transition between θ_{dry} and θ_{wet}. The particular values used for θ_{dry} and θ_{wet} depend somewhat on the thickness of the upper segments (Idso et al., 1975), and a more elaborate equation can be written (Eshel and Curry, 1980). However, as long as the θ_{dry} and θ_{wet} are appropriate for the segment thickness, Equation 5 should provide a simple, accurate simulation.

Angle Factors for Thermal Radiation Exchange

The angle factor, F_{12}, is defined as the fraction of the thermal radiation emitted by a first surface that is intercepted by a second (Gebhart, 1961). Referring to Figure 4, simple approximations for the various angle factors for radiation exchange between the vegetation, soil segments, and sky can be derived.

From soil to vegetation. Referring to Figure 4, if the plants are large enough to form a closed canopy (s-w <= 0), then all radiation emitted by the soil must be absorbed by the vegetation. Even when the plants are small, however, we shall assume that the radiation emitted from soil segments beneath the vegetation rows impinges on the vegetation. For soil segments between the rows, note that the angle β_1 would be almost the same for any point on the soil surface between the rows. Therefore:

$$F_{gvj} = 1.0 \quad \text{if } s - w \leq 0 \text{ for all } j \tag{6a}$$

$$F_{gvj} = 1.0 \quad \text{if } x_j \leq w/2 \text{ or if } x_j \geq s - w/2 \tag{6b}$$

$$F_{gvj} = (\pi - \beta_1)/\pi \quad \text{if } w/2 < x_j < s - w/2 \tag{6c}$$

where:

$$\beta_1 = 2 \text{ Arctan } [(s - w)/(2y)] \tag{7}$$

From vegetation to vegetation. Referring again to Figure 4, note that to a first approximation, β_2 does not change very much for any point on the side of a row. Therefore the angle factor for one row of vegetation viewing another row is:

$$F_{vv} = \left(\frac{y}{y + w}\right) \left(\frac{\beta_2}{\pi}\right) \tag{8}$$

where:

$$\begin{aligned} \beta_2 &= 2 \text{ Arctan } [y/(2(s - w))] \text{ if } s - w > 0 \\ \beta_2 &= \pi \text{ if } \quad s - w \leqslant 0 \end{aligned} \tag{9}$$

From vegetation to soil. For a closed canopy ($s-w \leqslant = 0$), the fraction of the radiation emitted by a vegetation row that impinges on the jth soil segment must be the ratio between the area of the soil segment to that of the vegetation row. This also contains the assumption that the lower shaded leaves are at the same temperature, T_v, as the upper sunlit leaves and therefore are emitting thermal radiation at the same rate. Similarly, when the canopy is not closed, those soil segments beneath the rows must still receive radiaion from the vegetation row in proportion to their respective areas. For those soil segments located between the rows, the average angle factor from the side of a row to the soil between the rows is β_3/π. Soil segments adjacent to a row must receive more thermal radiation than segments midway between the rows. However, as a first approximation, it is assumed that β_3 is appropriate for all segments, and that the angle factor for the between-row segments is β_3/π weighted for the fraction of the leaf area that is side row and for the fraction of the between row area occupied by one segment. Therefore:

$$F_{vgj} = \Delta x/[2\ (y + w)] \text{ for all } j \text{ if } s - w \leqslant 0 \tag{10a}$$

$$F_{vgj} = \Delta x/[2\ (y + w)] \text{ if } x_j \leqslant w/2 \text{ or if } x_j \geqslant s - w/2 \tag{10b}$$

$$F_{vgj} = \left(\frac{y}{y + w}\right)\left(\frac{\beta_3}{\pi}\right) \left(\frac{\Delta x}{x_k - x_\ell}\right) \text{ if } w/2 < x_j < s - w/2 \tag{10c}$$

where:

$$\beta_3 = \text{Arctan}\ [2(s - w)/y] \quad (11)$$

From air (sky) to vegetation. Over the row all sky radiation impinges on the vegetation. Again referring to Figure 4, note that because the sky and soil are parallel planes, that the fraction $(\pi - \beta_1)/\pi$ reaches the sides of the row. Therefore, weighting for the respective areas of row top and sides yields:

$$F_{av} = \frac{w + (s - w)(\pi - \beta_1/\pi)}{s} \quad (12)$$

From air (sky) to soil. Because the soil and sky are infinite parallel planes, any thermal radiation emitted by the sky that does not impinge on the vegetation must impinge on the soil. Therefore, proportioning for the area of an individual segment to the whole between row area:

$$F_{agj} = (1 - F_{av})\ \Delta x/(x_k - x_\ell) \quad \text{if } w/2 < x_j < s - w/2 \quad (13)$$

$$F_{agj} = 0 \quad \text{if } x_j \leqslant w/2 \quad \text{or} \quad \text{if } x_j \geqslant s - w/2 \quad (13)$$

From soil to air. Similarly, any radiation emitted by the soil that does not impinge on the vegetation must reach the sky. Therefore:

$$F_{gaj} = 1 - \sum_{j=1}^{J} F_{gvj} \quad (14)$$

From vegetaion to air (sky). Similarly, any radiation emitted by a row of vegetation that does not impinge on another row or on the soil must reach the sky. Therefore:

$$F_{va} = 1 - F_{vv} - \sum_{j=1}^{J} F_{vgj} \quad (15)$$

Thermal Radiation

The thermal radiation coming down from the sky is occasionally measured, and can be used as an input if available. Usually, however, it must be predicted from other weather parameters. If air temperature and vapor pressure are available, the clear sky model of Idso (1981b) is an accurate predictor. The equation for computing the clear sky emmittance is:

$$\varepsilon_a = 0.70 + 5.95 \times 10^{-4} e_a \exp[1500/(T_a + 273.16)] \quad (16)$$

If additional data about cloud amount and type are available (such as regularly recorded by National Weather Service Observers) then the method of Kimball et al. (1982) provides additional accuracy. Their equation for predicting sky radiation is:

$$R_a = \varepsilon_a \sigma T_a^4 + \tau_8 \sigma \sum_i^N A_i \varepsilon_i f_{8i} (T_i + 273.16)^4 \quad (17)$$

where σ is the Stefan-Boltzmann constant (5.6697 x 10-8 $W/m^2 \cdot K^4$), N is the number of cloud layers, A_i is the fraction of sky covered by the ith cloud layer, and ε_i is the emittance of the ith cloud layer (1.0 unless have cirrus or cirrostratus; then 0.5). The temperature of the ith cloud layer, T_i, is computed from:

$$T_i = T_a - 0.065 z_i \quad (18)$$

where z_i is the cloud layer altitude. The cloud radiation is assumed to be transmitted to the earth's surface in the 8-14 μm atmospheric window. The window emittance in the zenith direction, ε_{8z}, can be predicted from (Idso, 1981b):

$$\varepsilon_{8z} = 0.24 + 2.98 \times 10^{-6} e_a^2 \exp[3000/(T_a + 273.16)] \quad (19a)$$

The zenith emittance can be adjusted to hemispherical using (Idso, 1981a):

$$\varepsilon_8 = \varepsilon_{8z}(1.4 - 0.4 \varepsilon_{8z}) \quad (19b)$$

and then the window transmittance, τ_8, is obtained from

$$\tau_8 = 1 - \varepsilon_8 \quad (19c)$$

The fraction of the black body radiation emitted by a cloud that is within the 8-14μm band, f_{8i}, is computed from:

$$f_{8i} = -0.6732 + 0.6240 \times 10^{-2} (T_i + 273.16) - 0.9140 \times 10^{-5} (T_i + 273.16)^2 \quad (20)$$

The thermal radiation emitted by the vegetation can be computed from:

$$R_v = \varepsilon_v (p/s) \sigma (T_v + 273.16)^4 \quad (21)$$

where the p/s factor scales the area of the vegetation row to unit land area. It is related to the leaf area index. Similarly, the thermal radiation emitted by the jth soil segment is:

$$R_{gj} = \varepsilon_{gj} (\Delta x/s) \sigma (T_{gj} + 273.16)^4 \quad (22)$$

where the $\Delta x/s$ factor scales the segment area to unit land area. The emittance of the vegetation, ε_v, is a constant plant parameter. The emittance of a soil segment, on the other hand, can vary with the moisture content of that segment using the empirical equation:

$$\varepsilon_{gj} = 0.90 + 0.08\ (\theta/\theta_s) \qquad (23)$$

Ignoring reflections, the net thermal radiation absorbed by the vegetation can be written:

$$R_{nv} = \varepsilon_v F_{av} R_a + \varepsilon_v \sum_{j=1}^{J} F_{gvj} R_{gj} - (1 - \varepsilon_v F_{vv})\ R_v \qquad (24)$$

where the first term is the radiation from the sky, the second term is the sum of the radiation from all the soil surface segments, and the third is the radiation emitted by the vegetation that is not absorbed by other rows.

The net radiation absorbed by the jth soil surface segment can be computed from:

$$R_{gnj} = \varepsilon_{gj}\ F_{agj}\ R_a - R_{gj} + \varepsilon_{gj}\ F_{vgj}\ R_v \qquad (25)$$

where the first term is the absorbed sky radiation, the second is the radiation emitted by the soil segment, and the third is the radiation from the vegetation.

Similarly, the net radiation absorbed by the air above the crop can be computed from:

$$R_{an} = -R_a + \sum_{j=1}^{J} F_{gaj}\ R_{gj} + F_{va}\ R_v \qquad (26)$$

where the first term is the downward sky radiation, the second is the sum of the radiation from all the soil segments, and the third is the radiation from the vegetation.

In anticipation of solving Equations 1 and 2, Equations 21 and 22 need to be linearized. This can be accomplished following the method of Kimball (1981). Briefly, Equations 21 and 22 can be expressed:

$$R_v = R^o{}_v + \delta_{R_v}\ (T_v - T^o{}_v) \qquad (27)$$

$$R_{gj} = R_{gj}{}^o + \delta_{R_{gj}}\ (T_{gj} - T_{gj}{}^o) \qquad (28)$$

where $T_v{}^o$ and $T_{gj}{}^o$ are "old" temperatures from a previous iteration. The $R_v{}^o$ and $R_{gj}{}^o$ are "old" fluxes computed using $T_v{}^o$ and $T_{gj}{}^o$ in Equations 21 and 22. The δ_{Rv} and δ_{Rgj} are the derivatives with respect to temperature as given by:

$$\delta_{R_v} = \frac{dR_v}{dT} = 4\varepsilon_v (p/s) \sigma (T_v{}^o + 273.16)^3 \quad (29)$$

$$\delta_{R_{gj}} = \frac{dR_{gj}}{dT} = 4\varepsilon_{gj} \ (\Delta x/s) \ \sigma \ (T_{gj}{}^o + 273.16)^3 \quad (30)$$

To simplify later notation, it is convenient to define the following shortening variables.

$$Y_v = R_v{}^o - \delta_{Rv} T_v{}^o \quad (31)$$

$$Y_{gj} = R_{gj}{}^o - \delta_{R_{gj}} T_{tj}{}^o \quad (32)$$

$$Y_{nv} = \varepsilon_v F_{av} R_a + \varepsilon_v \sum_{j=1}^{J} F_{gvj} Y_{gj} - (1 - \varepsilon_v F_{vv}) \ Y_v \quad (33)$$

$$Y_{gnj} = \varepsilon_{gj} F_{agj} R_a - Y_{gj} + \varepsilon_{gj} F_{vgj} Y_v \quad (34)$$

Soil Heat Flux

The flux of heat conducted down from the surface of each of the soil surface segments is computed using the conduction transfer function approach (Kusuda, 1969; Peavy, 1978; Kimball, 1982). With this method a set of coefficients are used to compute the soil surface heat flux at a given time from the flux for the previous time and the surface temperatures for several previous times. The method has the advantage over the more commonly used finite difference approach in that time steps of about an hour can be used, rather than just a few minutes, which results in large savings in computer time. A disadvantage is that the thermal conductivity must be constant with time (but not with depth), which means that a different set of coefficients must be used for every different soil moisture profile. However, by computing several sets of coefficients for a representative range of soil moisture profiles beforehand and storing them for later use, it probably will be possible to predict soil heat flux with sufficient accuracy using the set that corresponds to the most similar soil profile. Then that set will be used for the next several hours until another set whose profile is more similar will be used.

Following Peavy (1978) and Kimball (1982), the soil heat flux for the jth segment can be written:

$$G_{j,t} = \Sigma_c G_{j,t-1} + \sum_{m=1}^{M} [B_{1,m}(T_{gj,t-m+1} - T_{gI})] \quad (35)$$

where the B's are the conduction transfer functions, $G_{j,t-1}$ is the soil heat flux for the previous time, t-1, $T_{gj,t-m+1}$ is the temperature of the jth soil surface segment at time t-m+1, and T_{gI} is the soil temperature at the bottom of the profile. For most work T_{gI} can be regarded as a constant soil parameter, but for other work it may be more appropriate to represent T_{gI} by an annual sinusoidal wave.

Note in Figure 1 that it is assumed that no horizontal flow of heat occurs. For adjacent segments with large temperature differences, such as a shaded next to a sunlit segment, some horizontal flow must occur. However, if the surface segments are made relatively thin, vertical flow must predominate, and this must be a safe assumption.

If Σ_{j1} and Σ_{j2} are defined as

$$\Sigma_{j1} = \sum_{m=2}^{M} B_{1,m} T_{gj,t-m+1} \qquad (36)$$

$$\Sigma_{j2} = T_{gI} \sum_{m=1}^{M} B_{1,m} \qquad (37)$$

then the term containing the current temperature can be written by itself as follows.

$$G_{j,t} = B_{1,1}\, T_{gj,t} + \Sigma_{j1} - \Sigma_{j2} + B_c G_{j,t-1} \qquad (38)$$

Convection

Convection of sensible and latent energy away from the vegetation and the soil surface segments can be written:

$$H_v = Ch_a\,(T_v - T_a)\,(p/s) \qquad (39)$$

$$H_{gj} = Ch_a\,(T_{gj} - T_a)\,(\Delta x/s) \qquad (40)$$

$$E_v = \mu h_v\,(e_v - e_a)\,(p/s) \qquad (41)$$

$$E_{gj} = \mu h_a\,(e_{gj} - e_a)\,(\Delta x/s) \qquad (42)$$

where C is the volumetric heat capacity of the air which is nearly constant (1210 J/m3.C) and $\mu = (\rho_a M_w)/(PM_a) = M_w/(RT+273)$, which evaluates to 7.39×10^{-3} kg/kPa·m^3 at 20 C. The h_a is a turbulent transfer coefficient for air which can be computed from the wind speed using (Sellers, 1965, p. 151):

$$h_a = u_a \left[\frac{k}{\ln(z/z_o)}\right]^2 (1 - 50\ \mathrm{Ri})^{\pm 1/4} \qquad (43)$$

where u_a is the wind speed (m/s), k is the von Karman constant (0.42), z is the height of the wind speed observation (often 2 m), and z_o is the roughness length of the vegetation. Lacking data for a guayule crop, z_o (m) initially can be computed from an empirical equation relating roughness length to crop height, y (m) (from Sellers, 1965).

$$z_o = 0.2812\ y^{1.417} \qquad (44)$$

When a crop is first planted and y=0, a reasonable minimum value for z_o would be about 0.03.

The Ri in Equation (43) is the Richardson number which provides an atmospheric stability correction to the log wind profile appropriate for neutral conditions. The coefficients, 50 and 1/4, are from Lemon (1978), and they provide curves very close to those of Pruitt et al. (1973). The +1/4 is for positive Ri and vice versa. The Richardson number is computed from:

$$\mathrm{Ri} = \frac{g(\overline{T} - T_a)(z - z_o)}{(\overline{T} + 273)\ u_a^2} \qquad (45)$$

where $\overline{T}$ is the "surface" temperature. For the guayule crop a reasonable estimate of $\overline{T}$ is a weighted average of the temperatures of the vegetation and exposed soil segments.

$$\overline{T} = \frac{T_v\ (w + 2y) + \Delta x \sum_{j=\ell}^{k} T_{gj}}{w + 2y + x_k - x_\ell} \qquad (46)$$

The h_v in Equation 41 is the transfer coefficient between the air and the bottom of the stomatal cavities in the leaves. Therefore, it is influenced by the resistance of the stomates to vapor transfer. Defining resistances,

$$r_v = 1/h_v = r_a + r_s \qquad (47)$$

where $r_a = 1/h_a$ and r_s is the stomatal resistance (s/m). Judging by observations with other crops, the r_s for guayule is a function of the intensity of solar radiation and of the leaf water potential, as illustrated in Figure 5. Following Kimball (1973) the relationship can be written:

$$r_s = b_1 + \frac{b_2}{\phi S_a + b_3} \qquad (48)$$

where the b_1, b_2, and b_3 are empirical coefficients determined from measurements of leaf resistance over a range of solar intensity and soil water potential. These coefficients may or may not be the same for different varieties of guayule.

The ϕ in Equation 48 is a stomatal response function that closes the stomates and increases r_s in response to decreasing (negative) leaf water potentials. As a first approximation, the response can instead be related to the soil water potential or water content. A tentative relationship for ϕ is illustrated in Figure 6 and defined as follows:

$$\phi = (\Theta_s - \overline{\Theta})/(\Theta_s - \Theta_f \qquad \Theta_f < \overline{\Theta} \leqslant \Theta_s \qquad (49a)$$

$$\phi = 1.0 \qquad \Theta_c \leqslant \overline{\Theta} \leqslant \Theta_f \qquad (49b)$$

$$\phi = (\overline{\Theta} - \Theta_w)/(\Theta_c - \Theta_w) \qquad \Theta_w \leqslant \overline{\Theta} \leqslant \Theta_c \qquad (49c)$$

$$\phi = 0.0 \qquad \overline{\Theta} \leqslant \Theta_w \qquad (49d)$$

where Θ_w is the wilting point and Θ_f is the field capacity of the soil. Because the whole soil profile is not at the same water potential, the value of $\overline{\Theta}$ to be used in Equation 49 requires some special consideration. As a tentative definition, $\overline{\Theta}$, is taken as the average water content of those segments that contain roots.

$$\overline{\Theta} = \frac{\Sigma_i \; \Sigma_j \; \Theta_{ij} \; \Delta z_i \; \Delta x}{\Delta x \; \Sigma_i \; \Delta z_i} \qquad (50)$$

The e_v and e_{gj} in Equations 41 and 42 are related to the temperature and the water potential of the leaves and soil surface segment, respectively. Following Campbell (1977, p.28), they can be computed from:

$$e = e^* \exp\left[(2.16 \times 10^{-3} \; \psi)/(T + 273.16)\right] \qquad (51$$

where the saturation vapor pressure, e^*, is well described by the Tetens equation (Murray, 1967; Kimball, 1981)

$$e^* = 0.61078 \exp [(17.2694\ T)/(T + 237.30)] \tag{52}$$

The soil water potential of ⁄a the jth segment, ψ_j, can be calculated from the water content of that segment, as will be described in a later section. The leaf water potential depends on the soil water potential and the conductance of root membranes and xylem tubes in the roots and stem. The difference in potential is usually much greater between the inside of the leaf and the air outside than between the soil and the leaf, so only a small error should be incurred if it is assumed that the leaf water potential is a constant 300 J/kg less than the soil water potential. Therefore:

$$\psi_v = \overline{\psi} - 300 \tag{53}$$

where $\overline{\psi}$ is the soil water potential corresponding to the average soil water content defined by Equation 50.

If the vapor pressure of the air exceeds the vapor pressure of the soil surface, condensation rather than evaporation occurs at the soil surface. Similarly, if the vapor pressure of the air exceeds the saturation vapor pressure of the leaves (computed using T_v in Equation 52), then condensation or dew is forming on the leaf surfaces, and for this case the h_v=h_a because the stomatal resistance does not interfere. It is unlikely that there will be much dew formation in the arid regions that will probably be used for guayule production. However, in order not to leave a gap in the accounting, it is assumed that the dew runs down to the soil closest to the stem and is stored there.

In anticipation of solving Equations 1 and 2, Equations 41 and 42 need to linearized. Like the thermal radiation terms discussed previously, this can be accomplished following the method of Kimball (1981). Briefly, e_v and e_{gj} can be expressed:

$$e_v = e_v^o + \delta_{ev} (T_v - T_v^o) \tag{54}$$

$$e_{gj} = e_{gj}^o + \delta_{egj} (T_{gj} - T_{gj}^o) \tag{55}$$

where e_v^o and e_{gj}^o are "old" vapor pressures computed using the "old" temperatures, T_v^o and T_{gj}^o, in Equations 51 and 52. The δ_{ev} and δ_{egj} are derivatives with respect to temperature. According to Philip and de Vries (1957), the change of the relative humidity with respect to temperature in a soil is close to zero. The righthand expoential term containing ψ in Equation 51 is the relative humidity, so therefore, the derivative of Equation 51 with respect to temperature is the same as the derivative of Equation 52, the saturation vapor pressure, with respect to temperature. From Kimball (1981)

$$\delta_e = de^*/dT = 4098.03e^*/(T + 237.30)^2 \tag{56}$$

In order to shorten later notation, it is also convenient to define the following two shortening variables:

$$V_v = e_v^o - \delta_{ev} T_v^o \quad (57)$$

$$V_{gj} = e_{gj}^o - \delta_{egj} T_{gj}^o \quad (58)$$

Equations 41 and 42 are multiplied by the latent heat of vaporization, λ, to convert from water to energy fluxes in Equations 1 and 2. From Kimba (1981), λ can be computed from:

$$\lambda = 2.501 \times 10^6 - 2381T \quad (59)$$

where the T that is used is an "old" one from a previous iteration.

Solving the Energy Balance Equations

Utilizing Equations 3 through 59, the terms in Equations 1 and 2 can be written out in more detail. Then they can be rearranged so that the unknown vegetation temperature, T_v, and the unknown soil surface temperatures, T_{gj}, are factored out individually. Then for the vegetation:

$$T_v \left[-(1-\varepsilon_v F_{vv})\ \delta_{Rv} - Ch_a p/s - \lambda\mu\ h_v\ \delta_{ev} p/s\right]$$

$$+ T_{g1}\ (\varepsilon_v\ F_{gv1}\ \delta_{Rg1})$$

$$+ T_{g2}\ (\varepsilon_v\ F_{gv2}\ \delta_{Rg2})$$

$$+ \cdots$$

$$+ T_{gj}\ (\varepsilon_v\ F_{gvj}\ \delta_{Rgj})$$

$$+ \cdots$$

$$+ T_{gJ}\ (\varepsilon_v\ F_{gvJ}\ \delta_{RgJ})$$

$$= - S_v - Y_{nv} - (Ch_a\ p/s)\ T_a + (\lambda\mu h_v p/s)(V_v - e_a) \quad (6$$

And for the jth soil surface segment:

$$
\begin{aligned}
& T_v \, (\varepsilon_{gj} \, F_{vgj} \, \delta_{Rv}) \\
& + T_{g1} \, (0) \\
& + T_{g2} \, (0) \\
& + \\
& \quad \vdots \\
& + T_{gj} \, (- \delta_{Rgj} - Ch_a \, \Delta x/s - \lambda\mu \, h_a \, \delta_{egj} \, \Delta x/s - B_{1,1}) \\
& + \\
& \quad \vdots \\
& + T_{gJ} \, (0) \\
& = - S_{gj} - Y_{ngj} - (Ch_a \, \Delta x/s) \, T_a + (\lambda\mu \, h_a \, \Delta x/s) \, (V_{gj} - e_a) + \Sigma_{j1} \\
& \quad - \Sigma_{j2} + B_c G_{j,t-1}
\end{aligned}
\tag{61}
$$

When the equations for all of the soil segments are written, an interesting linear system of equations is created. The system can be written in matrix form as:

$$
\begin{Bmatrix}
a_{vv} & a_{1v} & a_{2v} \cdots & a_{jv} \cdots & a_{Jv} \\
a_{v1} & a_{11} & 0 \cdots & 0 \cdots & 0 \\
a_{v2} & 0 & a_{22} \cdots & 0 \cdots & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
a_{vj} & 0 & 0 \cdots & a_{jj} \cdots & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
a_{vJ} & 0 & 0 \cdots & 0 \cdots & a_{JJ}
\end{Bmatrix}
\begin{Bmatrix}
T_v \\ T_{g1} \\ T_{g2} \\ \vdots \\ T_{gj} \\ \vdots \\ T_{gJ}
\end{Bmatrix}
=
\begin{Bmatrix}
c_v \\ c_1 \\ c_2 \\ \vdots \\ c_j \\ \vdots \\ c_J
\end{Bmatrix}
\tag{62}
$$

where the a_{ij} matrix has its first row, first column, and diagonal filled, but all other elements are zero. The specific elements are defined as follows:

$$a_{vv} = -(1 - \varepsilon_v F_{vv})\ \delta_{Rv} - Ch_a\ p/s - \lambda\mu\ h_v\ \delta_{ev}\ p/s$$

$$a_{1v} = \varepsilon_v\ F_{g1v}\ \delta_{Rg1}$$

$$a_{2v} = \varepsilon_v\ F_{g2v}\ \delta_{Rg2}$$

$$a_{jv} = \varepsilon_v\ F_{gjv}\ \delta_{Rgj}$$

$$a_{v1} = \varepsilon_{g1}\ F_{vg1}\ \delta_{Rv}$$

$$a_{v2} = \varepsilon_{g2}\ F_{vg2}\ \delta_{Rv}$$

$$a_{vj} = \varepsilon_{gj}\ F_{vgj}\ \delta_{Rv}$$

$$a_{11} = -\ \delta_{Rg1} - Ch_a \Delta x/s - \lambda\mu h_a\ \delta_{eg1}\ \Delta x/s - B_{1,1}$$

$$a_{22} = -\ \delta_{Rg2} - Ch_a \Delta x/s - \lambda\mu h_a\ \delta_{eg2}\ \Delta x/s - B_{1,1}$$

$$a_{jj} = -\ \delta_{Rgj} - Ch_a \Delta x/s - \lambda\mu\ h_a\ \delta_{egj}\ \Delta x/s - B_{1,1}$$

$$c_v = -\ S_v - Y_{nv} - (Ch_a\ p/s)\ T_a + (\lambda\mu\ h_v p/s)(V_v - e_a)$$

$$c_1 = -\ S_{g1} - Y_{ng1} - (Ch_a\ \Delta x/s) T_a + (\lambda\mu h_a\ \Delta x/s)(V_{g1} - e_a) + \Sigma_{11} - \Sigma_{12} + B_c\ G_{1,t-1}$$

$$c_2 = -\ S_{g2} - Y_{ng2} - (Ch_a \Delta x/s) T_a + (\lambda\mu h_a \Delta x/s)(V_{g2} - e_a) + \Sigma_{21} - \Sigma_{22} + B_c\ G_{2,t-1}$$

$$c_j = -\ S_{gj} - Y_{ngj} - (Ch_a \Delta x/s)\ T_a + (\lambda\mu h_a \Delta x/s)(V_{gj} - e_a) + \Sigma_{j1} - \Sigma_{j2} + B_c\ G_{j,t-1} \tag{63}$$

Because there are so many zero elements, Equation 62 can be solved without resorting to matrix inversion. Using elementary row and column operations, the following solution can be derived:

$$T_v = \frac{c_v - \sum_{j=1}^{J} a_{vj}\, c_j/a_{jj}}{a_{vv} - \sum_{j=1}^{J} a_{vj}\, a_{jv}/a_{jj}}$$

$$T_{g1} = \frac{c_1 - a_{v1}\, T_v}{a_{11}}$$

$$T_{g2} = \frac{c_2 - a_{v2}\, T_{g1}}{a_{22}}$$

$$T_{gj} = \frac{c_j - a_{vj}\, T_{g(j-1)}}{a_{jj}} \qquad (64)$$

Inspecting Equation 64, the solution is seen to be a set of recursion equations with the temperature of each soil surface segment being computed from the temperature of the segment with the next smaller index. Equations 64 are not automatically the final solution, however. The matrix elements are based on initial guesses or prior estimates of T_v and the T_{gj}. As illustrated in Figure 2, after new values T_v and T_{gj} are obtained, a convergence test is made. If T_v and T_{gj} are not sufficiently close to the "old" values, T_v^o and T_{gj}^o, then T_v^o and T_{gj}^o are set equal to T_v and T_{gj} and Equations 62 are solved again. The process is repeated until convergence is attained. Because anlytical equations are used for the slopes (Equations 29, 30, and 56), convergence is generally rapid (Kimball, 1981).

Once T_v and T_{gj} are known, then they are substituted into the equations for the thermal radiation, sensible, latent, and soil heat fluxes. This yields the transpiration rate of the vegetation and the evaporation of each soil surface segment.

PHOTOSYNTHESIS

Previous workers have used various functions to relate photosynthesis to solar radiation intensity and soil water potential. Recently, Tanner and Sinclair (1982) have postulated that because water vapor and CO_2 follow essentially the same pathway into or out of the leaves, and because within a class of plants (C3 or C4) the CO_2 gradient is essentially constant, the photosynthetic rate is directly coupled to the transpiration rate adjusted for the vapor pressure deficit of the air. Their equation is:

$$P = E_v \frac{k}{e_a^* - e_a} \tag{65}$$

where k = .05 for C3 plants. Using their equation would make it easy to compute photosynthesis from this model since the transpiration rate is already known. However, experimental data are needed to determine the type of equation appropriate for predicting photosynthesis in guayule.

GROWTH AND BIOMASS AND RUBBER PRODUCTION

Once the photosynthetic rate can be predicted, the photosynthate must be partitioned among the various competing processes in the guayule plant. It can be anticipated that respiration will consume much while maintaining the plant. The rates of all the processes will depend on temperatures, water potentials, and other variables, and much additional laboratory and field data must be obtained in order to obtain relationships which can predict these processes in the guayule plant. In the meantime, Figure 2 illustrates how these functions can fit into this model of a guayule plant.

SUMMARY AND CONCLUSIONS

The mathematical framework for a computer model of guayule has been developed. Energy balance equations were written for the guayule vegetation and the soil surface which enable the prediction of plant temperatures, evaporation and transpiration. Soil moisture content and potential are accounted, and used to regulate rates of transpiration and evaporation. Photosynthesis is coupled to transpiration or to solar intensity. The model is organized so that plant temperatures and water loss are computed hourly, whereas plant growth and soil moisture redistribution occur at less frequent or daily intervals. The next development step is incorporation of daily rates of biomass and rubber production. Eventually it will be possible to predict guayule yields of biomass and rubber, as well as water use.

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PERSONNEL: B. A. Kimball

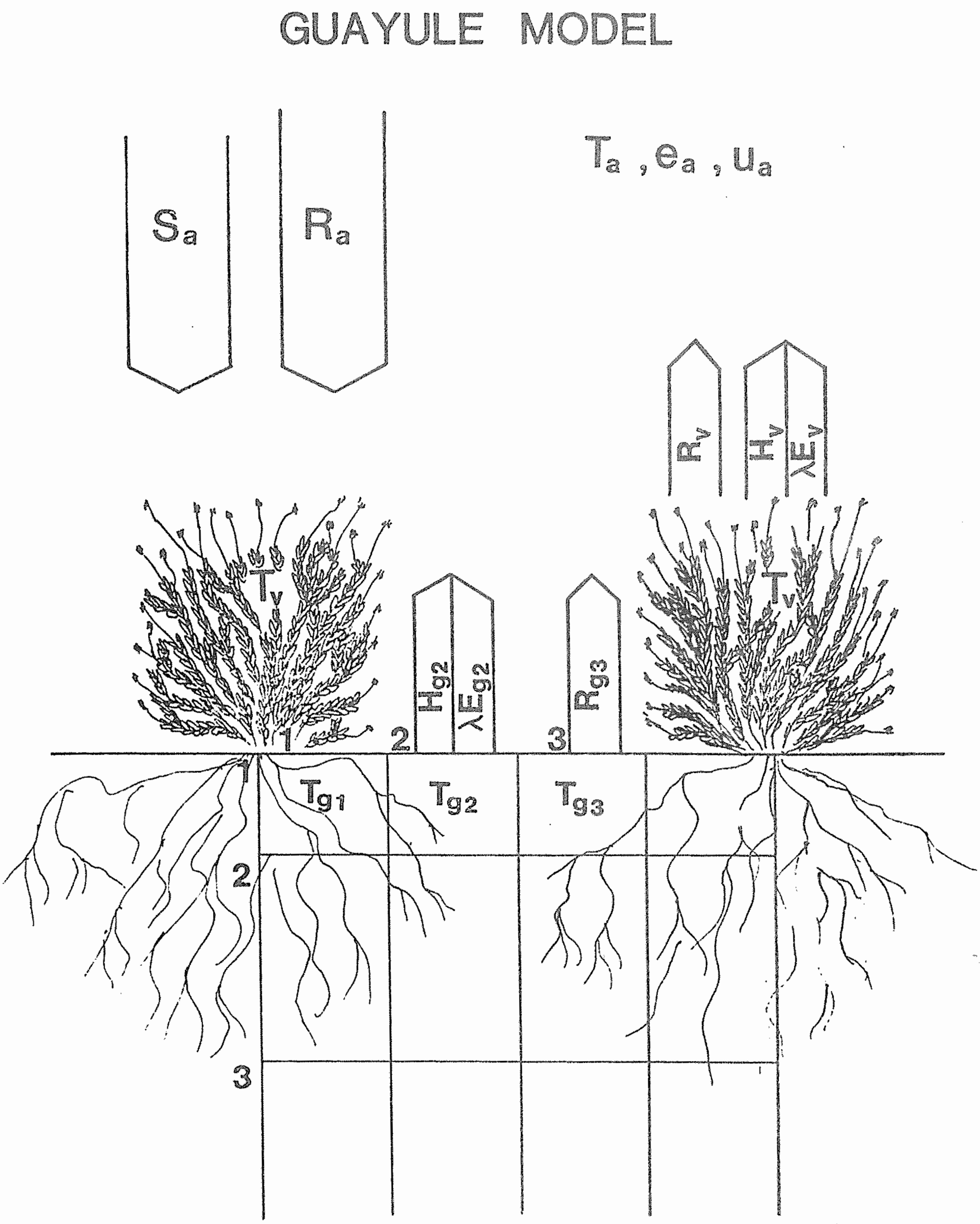
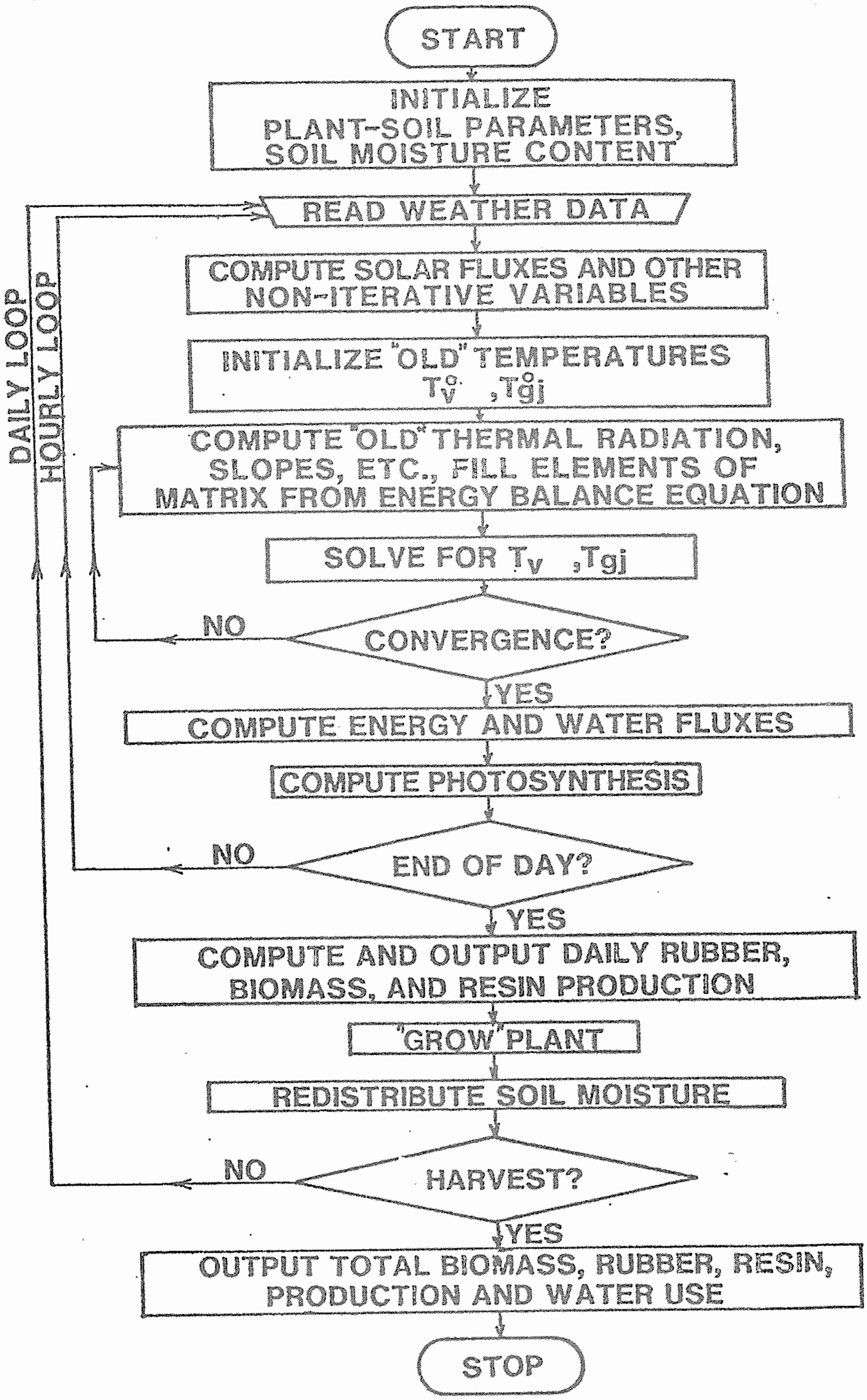


Figure 1. Schematic illustration of a guayule crop showing a cross-section through two rows. Also shown is the grid in the soil for computing soil moisture storage and flow using finite elements. The arrows represent flows of energy, with the direction of the arrows indicating the direction of positive flow.



GUAYULE MODEL

Figure 2. Overall flow diagram for directing the sequence of computation in the guayule model.

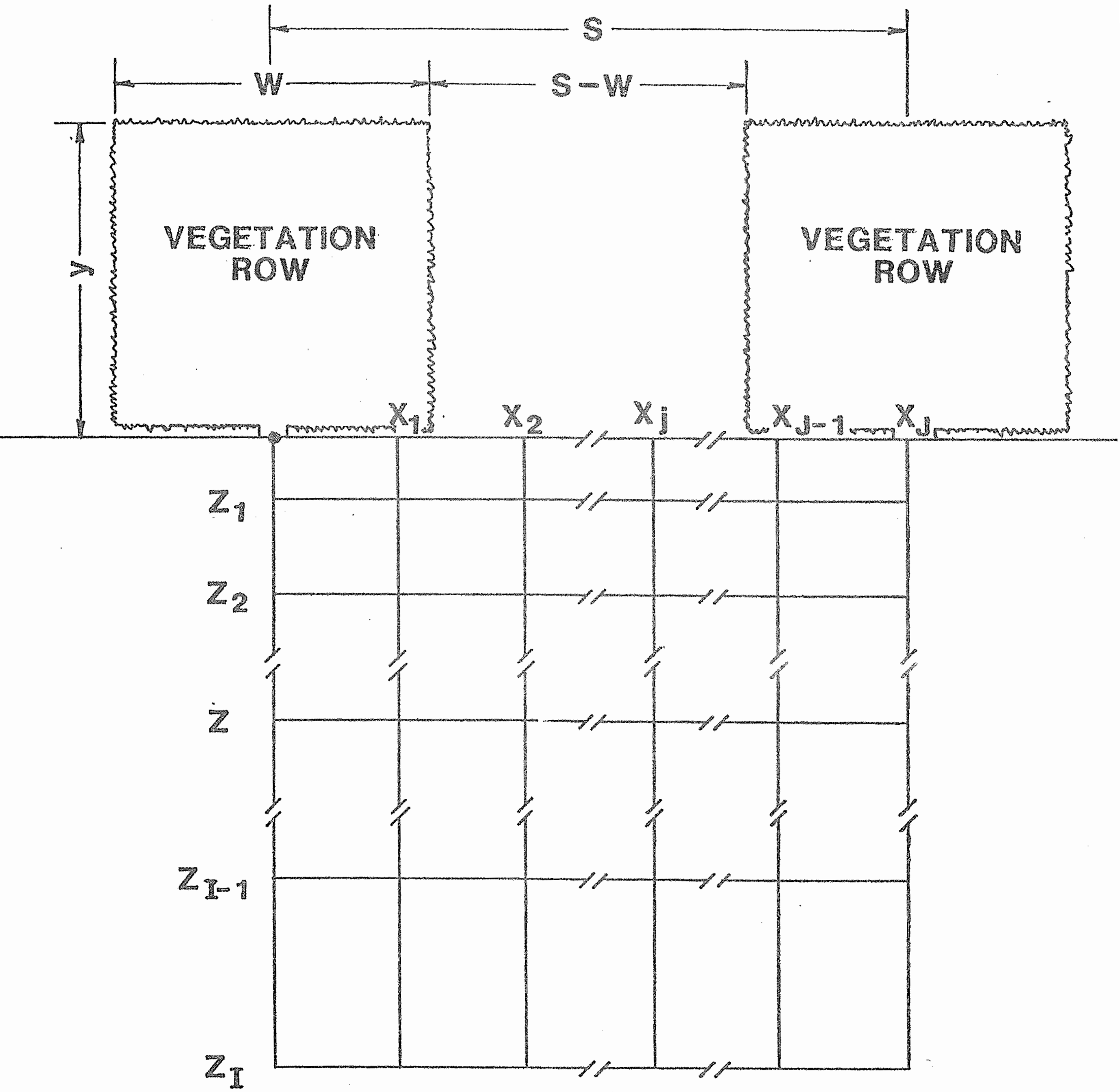


Figure 3. Illustration of the geometry and the notation used for the guayule vegetation row and for the soil grid between the rows.

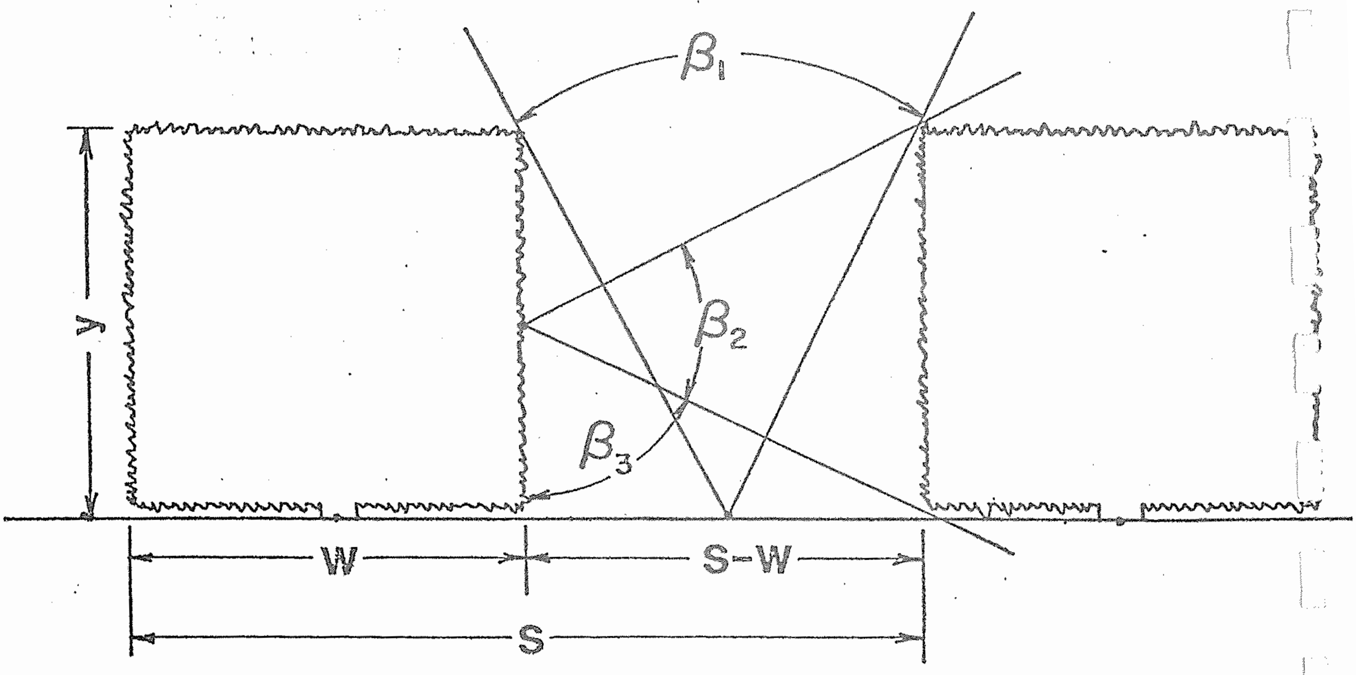


Figure 4. Definition of the β angles for deriving the angle factors of thermal radiation.

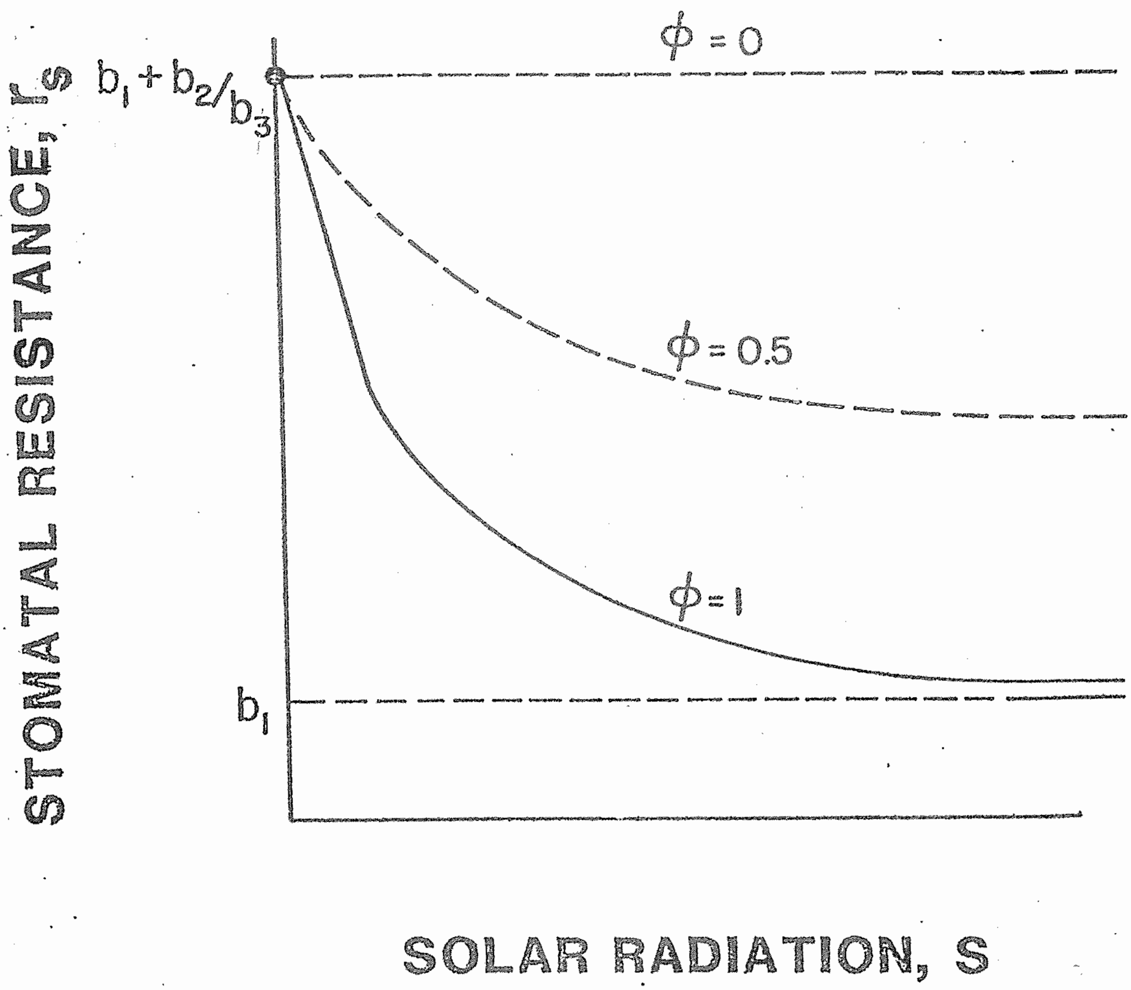


Figure 5. Stomatal resistance as a function of solar radiation and of a stomatal response function, ϕ.

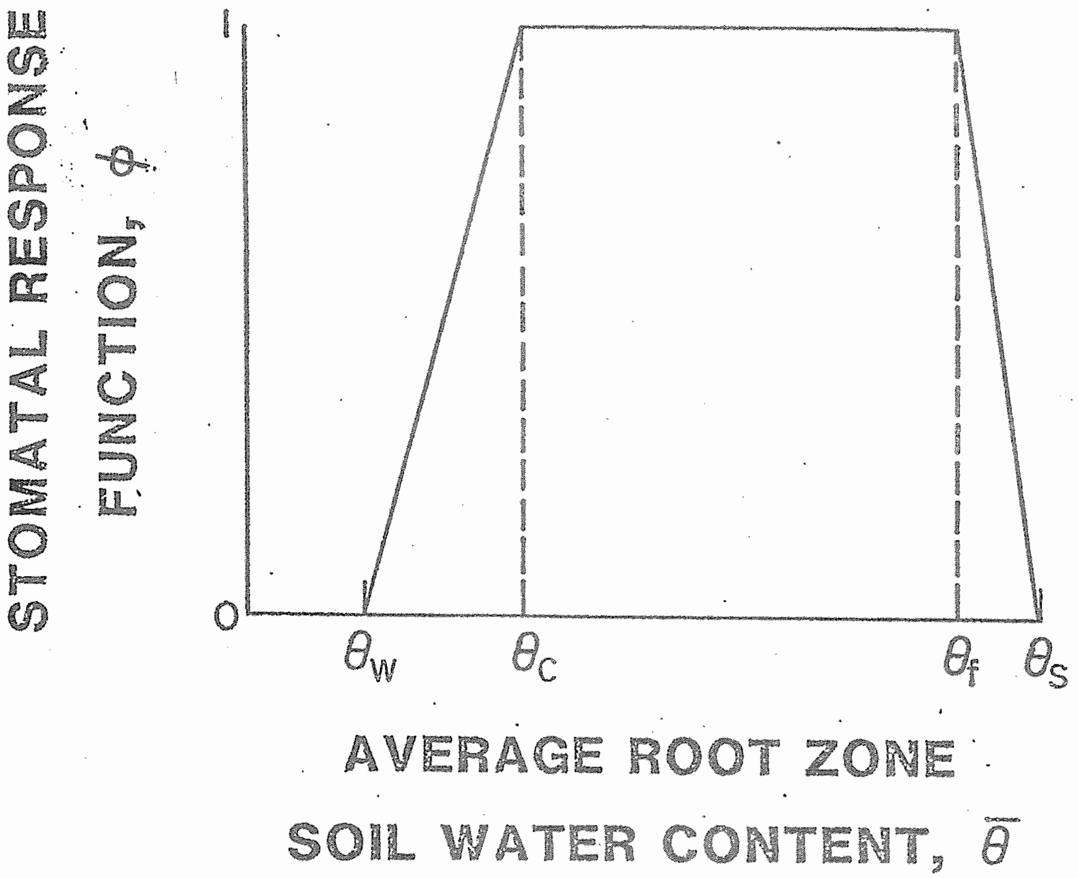


Figure 6. Stomatal response function versus average water content of the soil segments containing roots.

TITLE: DEVELOPING A CROP WATER STRESS INDEX FOR GUAYULE

NRP: 20740 CRIS WORK UNIT: 5510-20740-012

INTRODUCTION:

Very little information is available on the proper water management of guayule (Parthenium argentatum, Gray) to obtain maximum rubber yield per unit of water applied. The literature review by Hammond and Polhamus (1965) of some earlier investigations indicates that plant stress caused by soil water deficit can increase rubber production. Several approaches for controlling stress have been used. One is to grow the plant under a well-watered state for the first two years and then starve the plant of water the following two years to force rubber accumulation (Smith, 1942). Another is to impose alternate low and high moisture stresses, again based on the observation that production of rubber synthesizing tissues is be promoted during the non-stressed periods and rubber synthesis and storage during the stressed periods (Benedict et al., 1947). Highest rubber percentages were obtained with frequent and moderate periods of stress in the growth cycle (Retzger and Mogen, 1947).

Inconsistencies regarding soil moisture contents have been observed in that yields of shrub and rubber were high in a sandy loam soil at the higher moisture levels, whereas the highest rubber yields were obtained in a silty clay loam with the lower moisture levels (Hunter and Kelly, 1946). An explanation for this difference is based on the amount of available water and the rate at which stress was developed in the two types of soils. Retzer and Mogen (1947), also found that soil differences primarily associated with variations in soil moisture stress were the dominant factors influencing rubber production, and also important was the frequency and quantity of irrigation. Other factors directly or indirectly related to stress are temperature, nutrient availability, light intensity and season (Benedict, 1950).

At this point, we are interested in developing a simple and reliable means of following stress so that the stress-rubber production interrelation can be better defined. In the early work on guayule, soil water content determined either with gravimetric sampling or resistance blocks has been used as a basis of designating water stress. More recently, tensiometer and neutron moisture probes are being used to obtain the same type of relationship.

The approach at present with guayule is to use the plant itself as the indicator of stress. This has been accomplished mainly through stomatal conductance, and pressure and CO_2 chamber techniques. In many instances, existing instruments developed have been difficult to use on guayule because of its leaf morphology. Our measurements using the pressure chamber technique have shown that only small differences in potential could be observed between the well-watered and drought-induced plants.

Another method for estimating stress is through leaf temperature measurement. Remote sensing, infrared thermometric techniques have been applied to various economic crops to determine water stress (Idso et al., 1981, Jackson et al., 1981). For the crops studied the indexing procedure has been well correlated with yield. Since drought tolerance and possibly the water relation of guayule is unlike any of the crops used previously, the first question tha needed to be answered was whether the method of water stress indexing deve loped for other crops would be applicable to guayule under supplemental irrigation in an arid environment.

PROCEDURE:

Three-month-old guayule seedlings (for varieties, 593 and 11591) were transplanted in April 1981, on 1.8 x 3 m, (6 x 10 ft.) plots. Row spacing was 46 cm (18 in.) and plant spacing was 36 cm (14 in.), equivalent to 62,000 plants/hectare (25,000 plants/acre). There were four rows per plot with the two inner rows selected for temperature measurements. The two varieties were completely randomized within an irrigation unit which consisted of four replicated plots for each variety. Four aluminum access tubes were installed to a depth of 180 cm (6 ft.) per unit, two for each plant variety.

Three levels of water application were used:

(a) "wet" irrigation when 80% of the available water between the 10- to 170-cm soil profile was depleted;

(b) "medium" with 90% depletion and,

(c) "dry" with 95% depletion.

Available water is defined as the water between wilting point (=11%) and field capacity (=28%) for the Avondale clay loam. Water was applied with double-walled trickle irrigation tubing. Irrigation was started initially with buried lines, but gopher damage necessitated conversion to a surface system. Differential irrigation treatments began the last week in July when the transplants appeared to be well established.

Soil water contents were determined from 20- to 160 cm depth at 20-cm intervals with the Troxler Electronic Laboratories, Inc., and Campbell Pacific Nuclear Corp. neutron moisture probes. The equipment was calibrated in the same soil as the experimental plots. Moisture readings were taken two to three times per week in the spring through fall period, and once during the winter months.

Plant temperatures were taken with portable Telatemp and Everest Interscience infrared thermometers. Both instruments had a 3° field of view and spectral bandpass of 8- to 14 μ. The equipment readout was compared with a black-body reference absorber that was equipped with its own temperature readout and any temperature difference between the infrared thermometer and absorber readout was used to adjust the plant temperature measurement.

Initally, temperature averages of the west- and east oriented readings taken on the north-south oriented plant rows were used. Further investigation showed that similar results could be obtained with the sensor pointed vertically into the plant, so this method was selected in the later work. Six plants per plot were measured for temperatures on a regular basis between 12 and 1330 hours Mountain Standard Time. In some instances, hourly runs were made starting at near sunrise and continuing to sunset.

Vapor pressure deficit was determined 1 m above the crop with a battery-operated psychrometer.

Plant-air temperature differences versus vapor pressure deficits in well-watered conditions were used to develop the crop stress baseline following the method of Idso et al. (1981) for other types of crops. Crop stress indices for guayule of other soil moisture conditions were computed from the plant, air temperature's, and vapor pressure deficits.

RESULTS AND DISCUSSION:

The guayule plant temperatures responded to the moisture status and changes in soil. Plant minus air temperature values for the three irrigation treatments and two varieties as a function of time are presented in Figure 1. The 593 variety consistently showed a 0.5 to 1°C higher leaf temperature than the 11591 variety in all irrigation treatments. This behavior is not unique to gauyule as Mtui et al. (1981) noted different canopy temperatures for two hybrid lines of corn grown under the same conditions.

Plant temperature dropped rapidly following an irrigation, reached minimum values a few days after, and then increased almost linearly with time. Temperature difference of 14°C was observed between the well-watered and water-stressed plants. On a seasonal basis, plant temperature remained consistently above air temperature during the mid-December to March period even though adequate soil water was available. Further elaboration of such relation will be made in the discussion of stress index.

Other investigators (Idso et al. 1977) have applied the standard stress-degree-day (SDD) concept, where $(SDD)_{std} = (T_{plant} - T_{air})_{pm}$ and normalized SDD, where $(SDD)_{nor} = (T_{plant} - T_{air})_{pm}$ - constant, as basis for predicting crop yield. Data presented here could be used in a similar manner once the rubber yields yields have been established for the various irrigation treatments. The developers of the stress-degree-day have made further improvements and now have taken into account other meteorological parameters, particularly the vapor pressure deficit, to make the measurement universally applicable to the different climate zones.

Plant temperature variability was smaller in the well-watered and recently irrigated plots than in those plots undergoing long drying cycles; the coefficient of variation was less than 2% compared to greater than 3% as the soil water deficit increased. Aston and Van Bavel (1972) suggested that large temperature variability within a field signaled the onset of water deficit. Plant-air temperature differentials as a function of vapor pressure deficit for the varieties 593 and 11591 under well-watered conditions are presented in Figures 2 and 3, respectively. The slopes of 1.61 and 1.58 were similar for the two varieties, but the intercept for the 593 was approximately 0.7°C higher than the 11591. This goes along with the previously-cited observations in Figure 1, where the temperature-time data for the two varieties were given. The relations $\Delta T = 0.51 - 1.92$ VPD (alfalfa) and $\Delta T = 1.48 - 1.34$ VPD (soybeans) were obtained by Idso et al. (1981). The significance for the difference between the slopes and intercepts for the various crops is not apparent at present. Idso has been determining baseline curves for various plants (personal communication) and his results may give clues as to the reasons for the differences.

Under the arid environment, our measurements lacked points below vapor pressure deficits of 2.5 kPa, the high humidity range, so that the curve could not be completely defined. However, since values lower than 2 kPa are seldom encountered in the low humidity Phoenix area (except possibly in the early mornings or rainy conditions), the experimental curves should adequately serve our needs.

Computed stress indices of the 593 variety for the "wet" and "dry" treatments based on adjusted upper temperature limit are shown in Figures 4 and 5, respectively, together with the fraction available water in the soil. For the January to December period, the wet plots received 11 irrigations (165.2 cm) and the dry plots only six (100.0 cm). Rainfall during this period was 17.3 cm. In both instances the stress indices rapidly decreased following irrigation, but an index of 0 was seldom reached in the dry treatment. The CWSI values increased linearly and very rapidly after the minimum region was reached.

The remaining available water was depleted almost at a constant rate after irrigation until approximately 0.15 was used, at which point the rate of change became curvilinear, and below 0.05 the rate of change abruptly decreased.

Crop water stress indices of greater than 1 were obtained particularly in the dry treatment. This variation could be caused by interference of the soil surface or other plant parts on the plant foliage temperature reading, an inadequate baseline, or the inability to determine a suitable upper temperature limit. Additional work is needed to resolve this behavior, such as the approach of Jackson et al (1981), which includes additional meteorological parameters.

A linear relation was obtained when the crop water stress index and fraction available water were compared (Figure 6). Such relatiship, when developed for a crop, should be useful in estimating the moisture status of the soil or the stress status of the plant when either of the two factors is known. Soil moisture records from past experiments could be used to assess the stress status of plants occurring at the time.

Besides the temperature readings taken between 1230 and 1330, measurements were occasionally made continuously on an hourly basis from near sunrise to sunset to follow stress patterns of plants through the day. Results are illustrated in Figure 7 covering the 0700 to 1900 hours for the two guayule varieties in the wet (=A) and dry (=a) treatments. The diagonally drawn base line can be used as a guide in delineating the stress and unstressed situations for some of the data points. The temperature differences between the foliage and air of the well-watered and moisture-depleted soil are dramatically different. Except for the early morning and late evening hours, the plant temperatures of the dry treatment were significantly above air temperature, whereas those for the well-watered plants were consistently below air temperature.

The plants during the hours between 7 to 9 (A to C) and 1500 to 1900 (I to M) were not fully exposed to sunlight and the plant temperatures were controlled primarily by environmental convective and radiative conditions and not necessarily by plant responses. Plant temperatures in the dry treatment went below air because of this and not necesasrily because of transpirational cooling.

Plant temperature difference peaked out at the 1200 and 1400 hours for both treatments. The hours between these two periods were normally used in making individual stress index computations. It appears that the 1000 to 1400 period could be used to establish the baseline since a range of vapor pressure deficits can be encountered over this time period. Water use behavior of the young guayule was determined for the two varieties from the frequently measured soil water contents. The water-use values based on soil water depletion are given in Figure 8. The evapotranspiration of Variety 593 was less than 11591 (127.1 cm vs 162.7 cm), and this difference was more discernable during the high water-use summer periods than other times. The 593 plants were smaller than the 11591 and as noted earlier, the temperature of the 593 was consistently less than the 11591, indicating less transpirational loss for the 593 than 11591 variety. Ehrler and Bucks (1981) found that water use of other varieties also differed one from another.

One must be careful in using and projecting water requirements of guayule from the data presented here. Of prime importance is that rubber yield has not been finalized; and possibly just as important is the fact that the relations were based on well-watered plants, which were needed to establish the baseline used for developing the stress index. In addition, summer temperatures were the highest recorded for this area. Water-use values for the "dry" treatment with six irrigations were 91.4 and 103.7 cm for Varieties 593 and 11591, respectively, and for the "medium" with seven irrigations were 112.7 and 118.9 cm. In terms of water application alone, Retzer and Mogen (1947) give water additions of from 76 cm to 127 cm for rubber production, a compromise between rubber percentage and shrub yield.

SUMMARY AND CONCLUSIONS:

The drought-tolerant guayule plant was found to behave in a manner similar to the other types of crops in regard to water stress and foliage temperature, so that concepts on yield and stress already developed for these crops could be adapted to guayule culture. Because rubber production appears to be one of stress (water) management, the remote sensing infrared thermometric technique seems ideally suited for determining the onset, duration and relief of stress; and by using the stress index approach similar to the stress-degree-day concept, rubber and other material production could be related to the timing and duration of stress. Undoubtedly, experiments are now underway or being contemplated by other organizations to relate yield to the amount and frequency of water applications. These investigations could profit greatly by using techniques described here for evaluating stress.

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PERSONNEL: F. S. Nakayama, D. A. Bucks, and J. M. Martinez

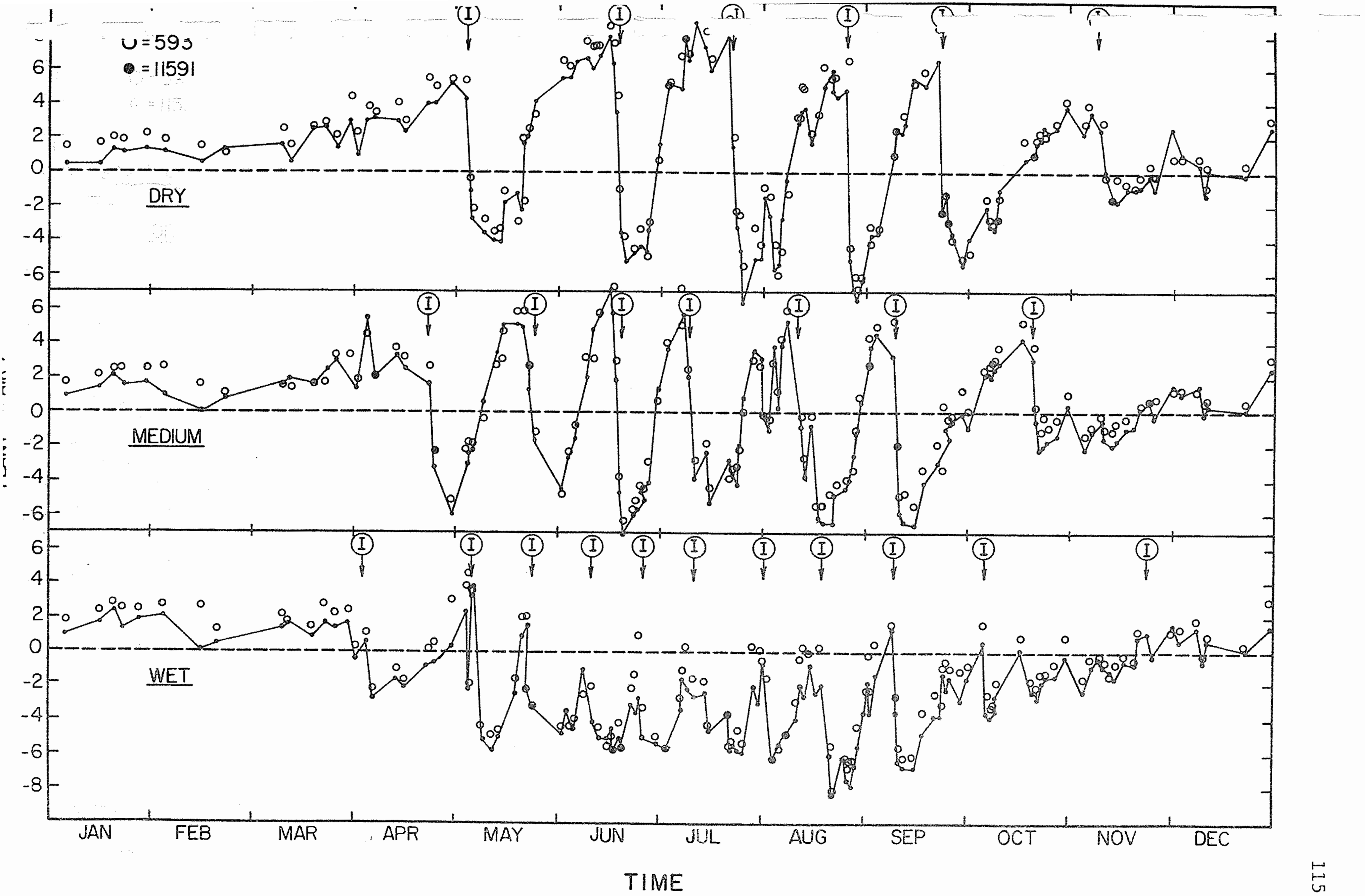

Figure 1. Plant-air temperature differences versus time for two guayule varieties.

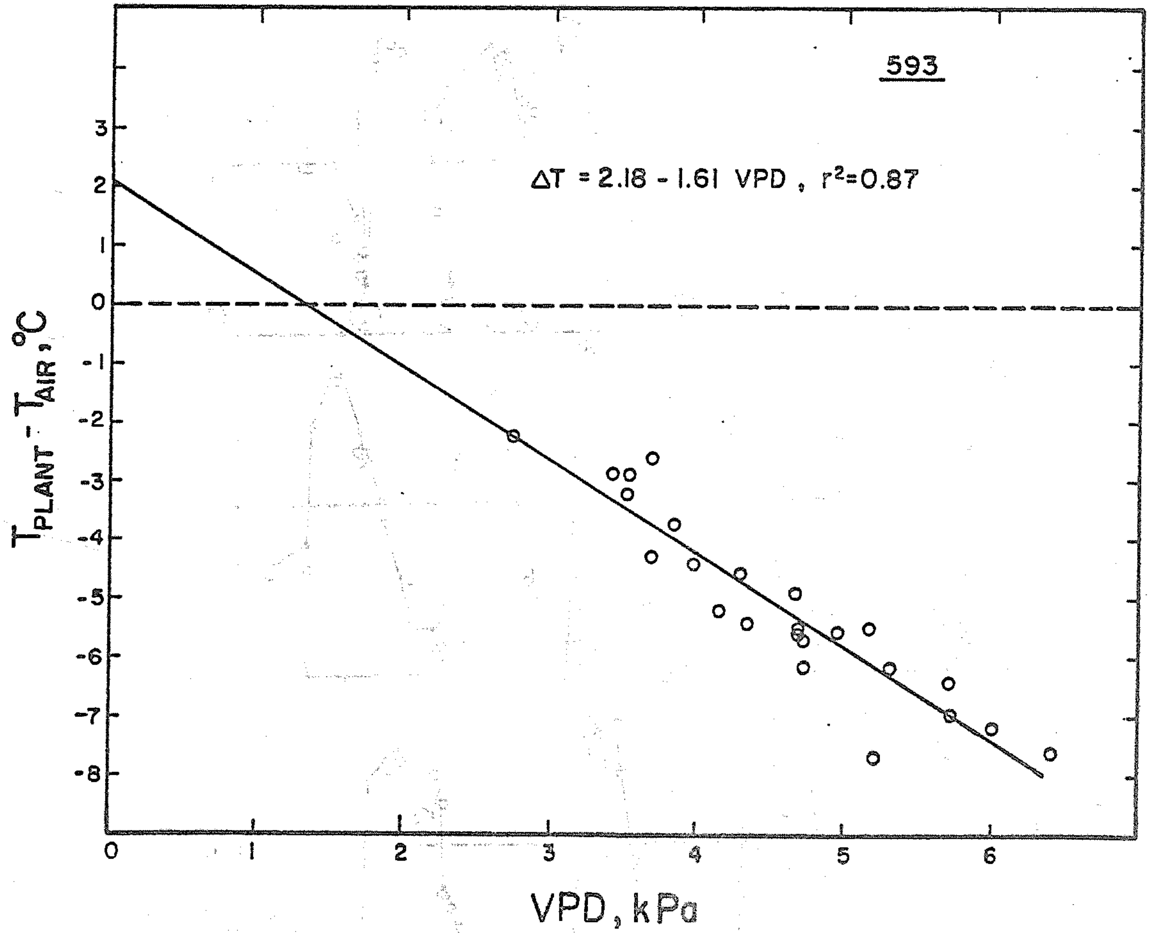

Figure 2. Plant minus air temperature differential versus vapor pressure deficit in well-watered plots for variety 593.

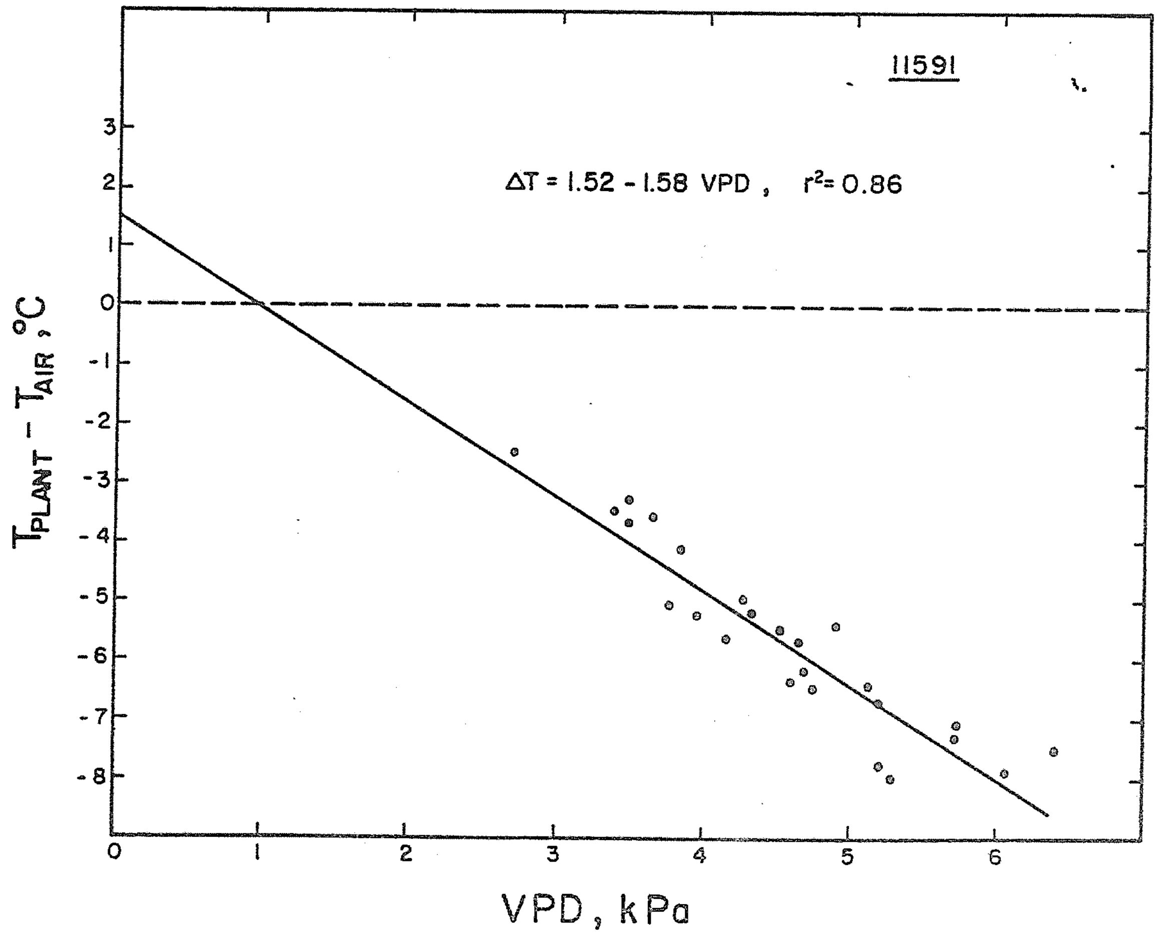

Figure 3. Plant minus air temperature differential versus vapor pressure deficit in well-watered plots for variety 11591

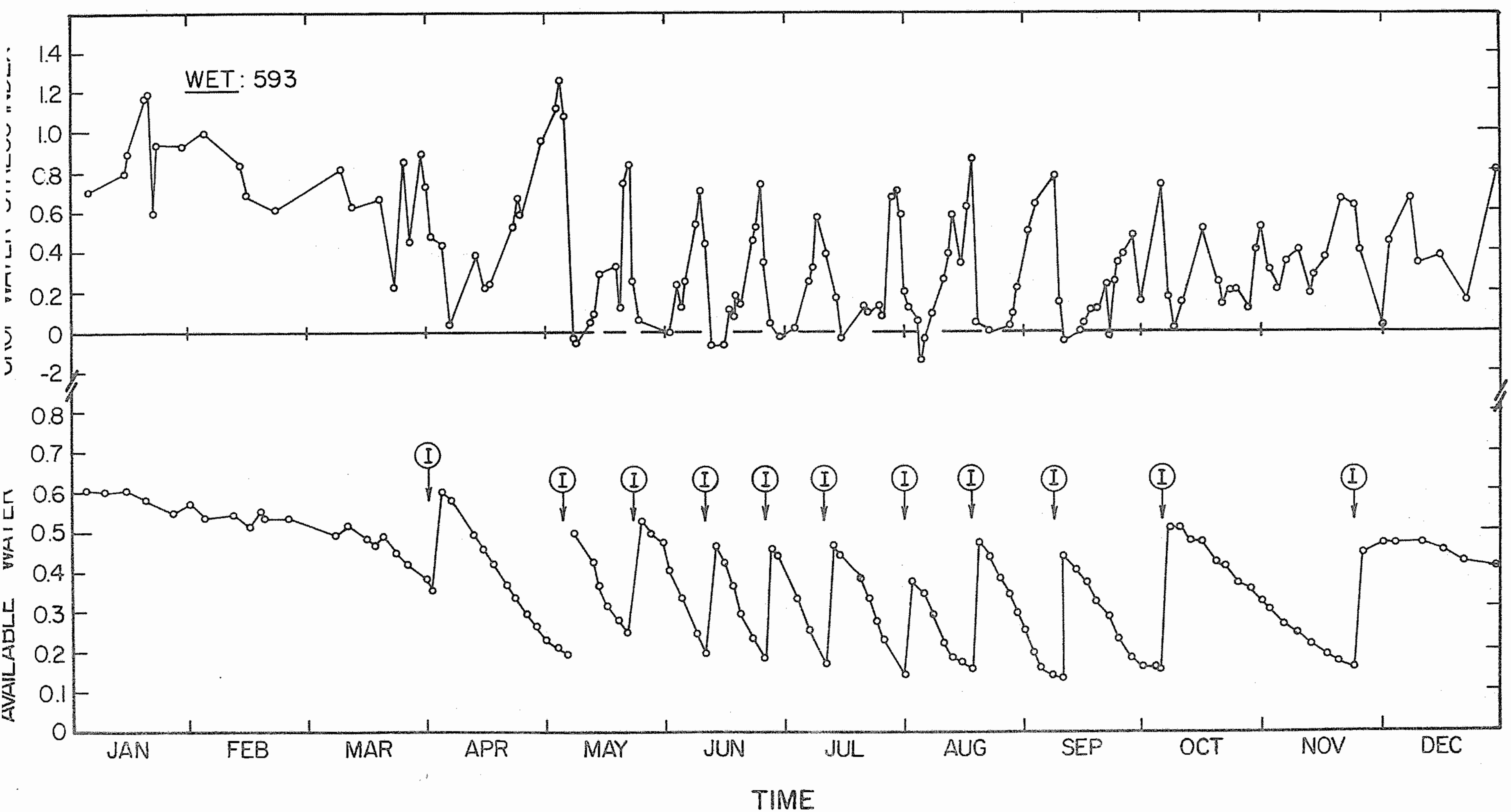

Figure 4. Relation between crop water stress index and fraction water available for variety 593 under wet treatment.

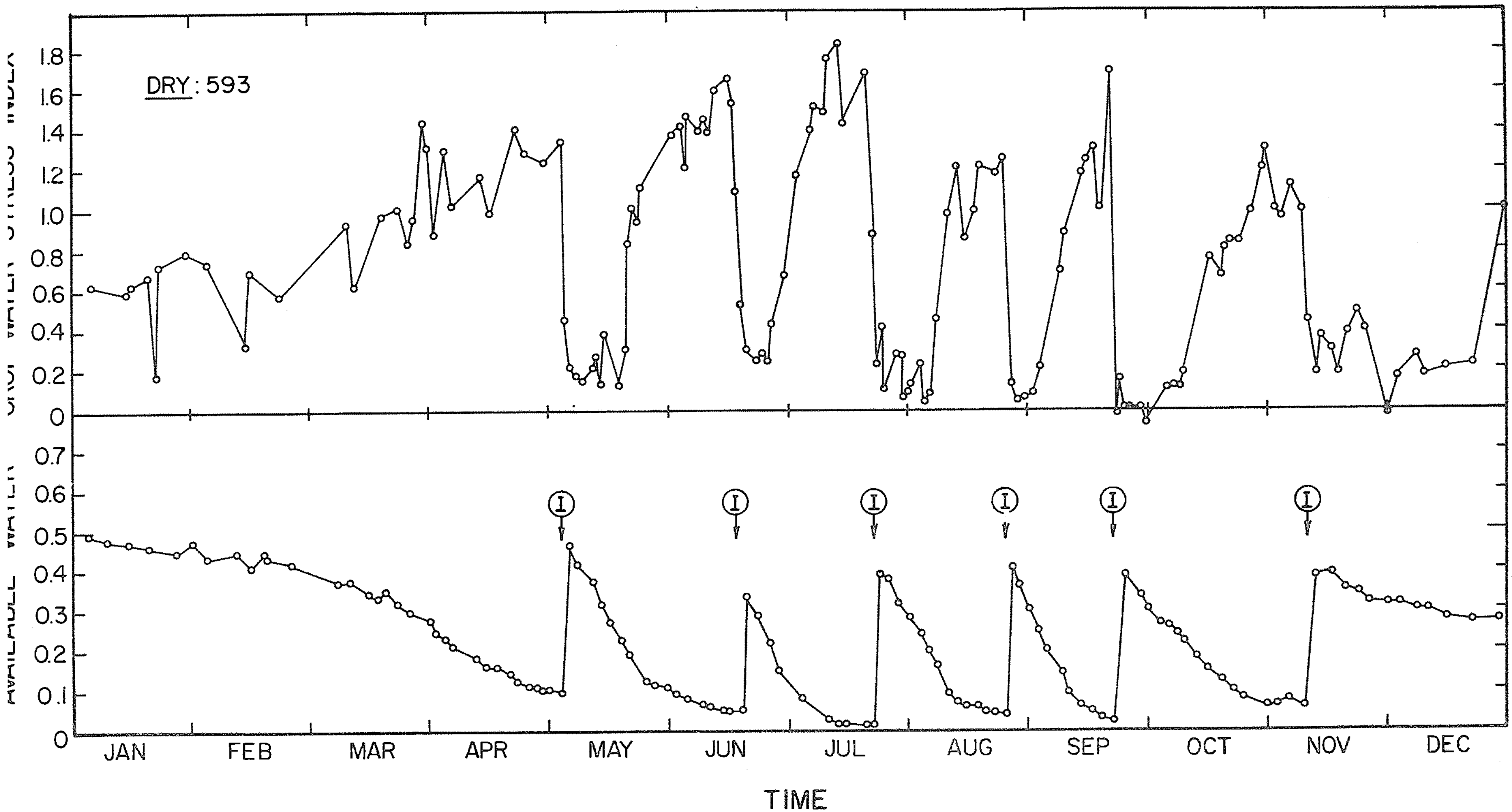

Figure 5. Relation between crop water stress index and fraction water available for variety 593 under dry treatment.

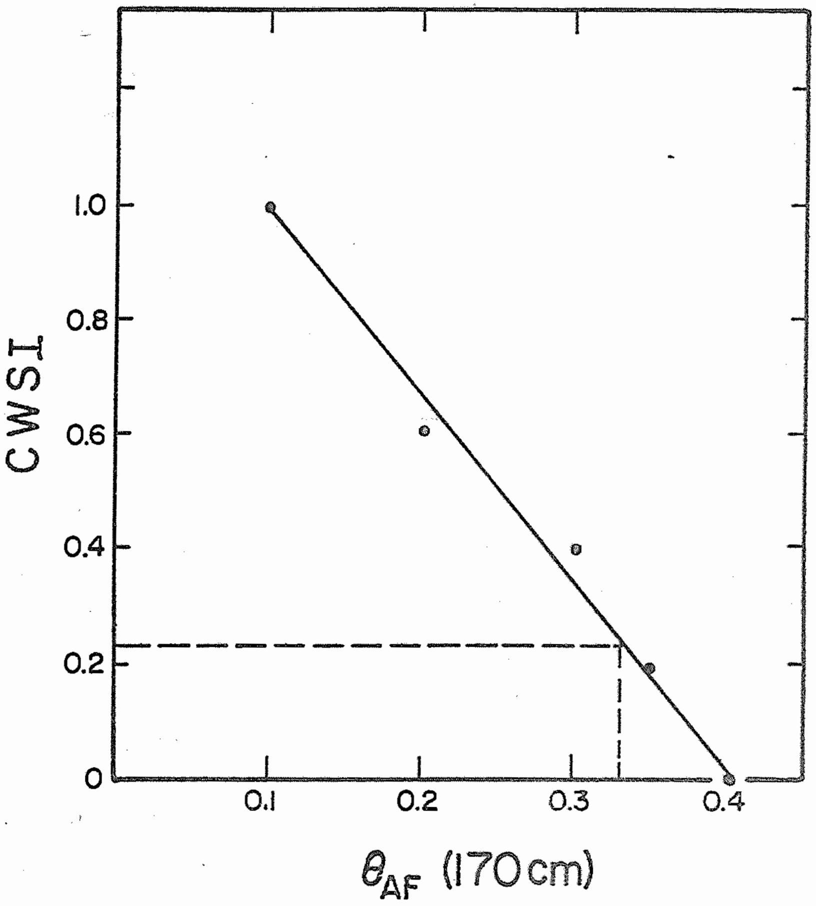

Figure 6. Relation between crop water stress index and fraction available water.

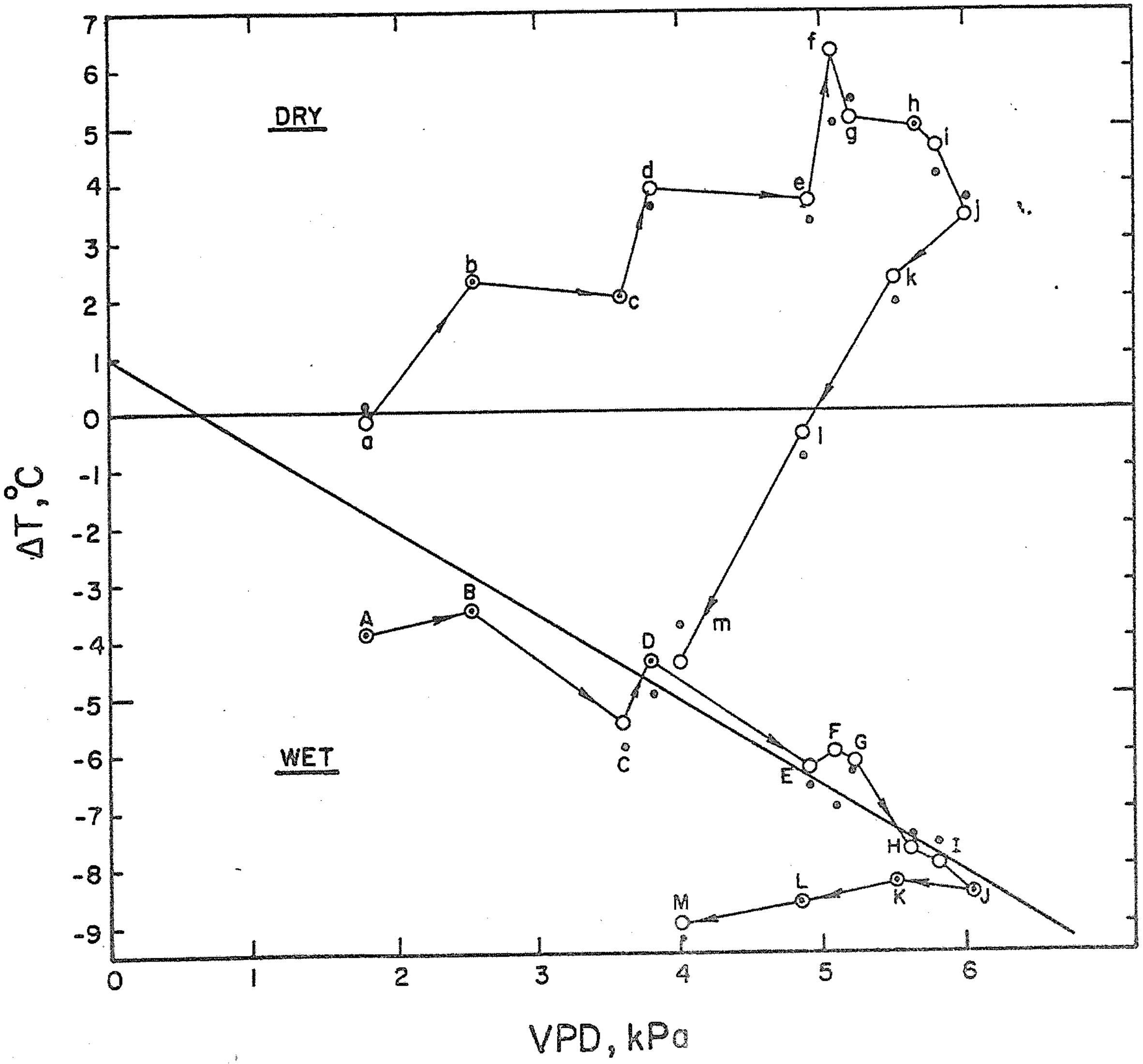

Figure 7. Temperature behavior patterns on a diurnal basis for two guayule varieties under two soil moisture regimes. (Open circle = 593 and solid circles = 11591 varieties). A=a=0700, B=b=0800...., M=m=1900.

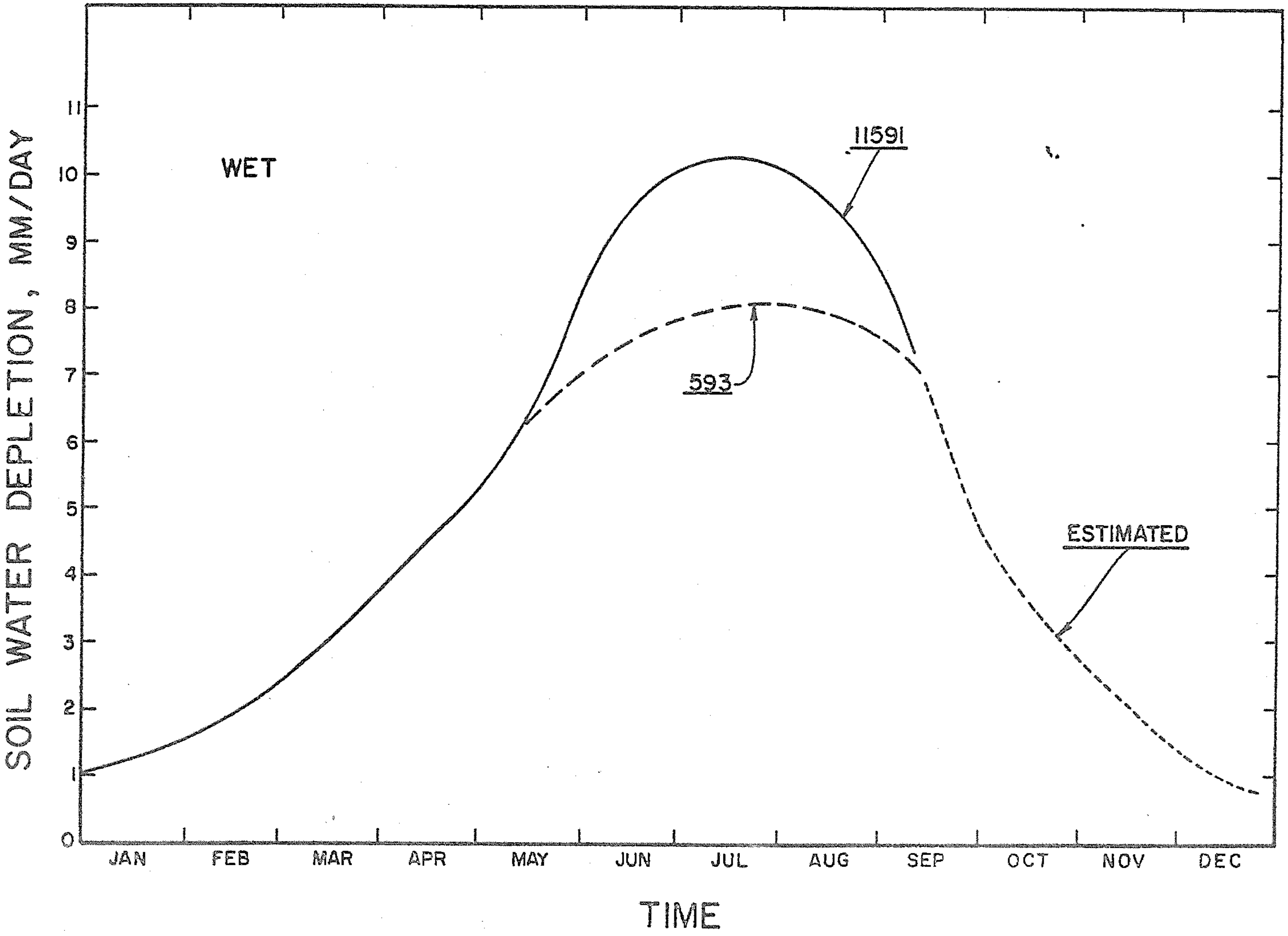

Figure 8. Soil moisture depletion rate for young guayule plant

TITLE: WATER AND AGRONOMIC MANAGEMENT FOR ECONOMICAL GUAYULE RUBBER PRODUCTION UNDER DIFFERENT CLIMATIC AND SOIL CONDITIONS

NRP: 20740 CRIS WORK UNIT: 5510-20740-012

INTRODUCTION:

Natural rubber is a commodity of strategic importance for all industrial countries. Currently, the United States imports all of this material from foreign sources, where supplies are obtained from the rubber tree (*Hevea brasiliensis*). *Hevea* grows only in tropical, lowland rain forests. Guayule (*Parthenium argentatum*) is the most promising plant available for natural rubber production within the continental United States. Demand for natural rubber is strong because of its elastic, resilient, tacky, and low heat buildup properties under stress. Most synthetic rubbers do not have these characteristics which are so important for automobile, heavy equipment, and airplane tires. Furthermore, world demand may exceed supply by the year 2000 or sooner.

Water requirement of the guayule plant is considered to be low. Native plants can survive and grow where rainfall is limited in the order of 380 mm. However, for commercial production, supplemental water application and other improved cultural practices would be needed to increase the net rubber per unit area. The effect of irrigation is very marked on plant structure (Lloyd, 1911). Rubber production is believed to occur during periods of limited growth caused by stress conditions such as drought, low temperature, and nutrient deficiencies (Benedict et al., 1947).

Kelley et al. (1945) in nursery cultivated plants found that well-watered plants had more growth, but less rubber content than those under water stress conditions. For transplant survival, however, moisturestressed plants had better survival rates than the less stressed plants. In field trials of 2-year old plants, Hunter and Kelley (1946) observed an inverse relation between rubber percentage and the dry weight of the shrub. Higher yields of rubber and shrub were obtained from plots maintained at high moisture levels in a sandy loam soil, whereas the opposite behavior occurred in a silty clay loam. Tingey (1952) reported similar trends in the effect of water levels, but his intermediate level of irrigation gave the highest rubber yield per unit area.

Benedict et al. (1947) noted that when guayule was grown under alternate low and high moisture stresses of 2- and 4-month durations each, the absolute rubber content increase was greater during periods of high than low moisture stresses. High stress periods should be long enough to maximize rubber production, but not so long that growth is entirely inhibited. Unfortunately, this experiment lasted only 14 months and the plants were not at an age when harvesting would normally occur. Retzer and Mogen (1947) reported that the highest rubber percentages were obtained from plants under frequent to moderate periods of stress, but higher rubber yields were present with the larger sized plants of lower rubber concentrations. For 2-year old shrubs, the best compromise appeared to be that of about 7 to 9% rubber with 4,500 to 7,800 kg of shrub/ha after applying 750 to 1,300 mm of water. Tingey and Clifford (1946) got higher rubber yields in the 12- to 14-month old plants with the heavier than moderately irrigated plants.

The Emergency Rubber Project (ERP) initially estimated water requirements for guayule based on the needs of other crops (McGinnies and Mills, 1980). Later experience showed that these estimates were too large after the stand were established. Rubber production was the highest when the plants were subjected to alternate periods of low and high water stress. The duration of these periods under climatic regimes and the optimum amount of water for different soils was not investigated. At present, there is little quantitative information on the effects of varying moisture stresses over long time periods on the rates of guayule growth and rubber production. The ERP research programs did not last long enough to obtain such information (Kelley, 1975).

All the preceding studies indicate that rubber production can be controlled either totally or partially by the moisture status in the guayule plant. Therefore, information on water requirements and rubber yield per unit volume of water are needed to optimize the scheduling of irrigations. The economics of rubber production could readily be developed from these data.

The following objectives have been established for this comprehensive irrigation water and agronomic management project:

(1) Determine water requirements, evapotranspiration estimates, and irrigation scheduling techniques for maximizing guayule rubber an resin production on a unit water and economic basis.

(2) Develop improved techniques for transplant establishment under various field conditions.

(3) Determine guayule irrigation and minimum and maximum fertility requirements on marginal agricultural land with limited surface and groundwater supplies.

Guayule plants have or will be planted at three locations in replicated, large field plots to see how climatic and soil variabilities affect yield and irrigation water management. Soil variables include a medium-textured, medium water holding capacity (Mesa); a heavy-textured, high water holding capacity (Brawley); and a coarse-textured, low water holding capacity (Yuma). Mesa and Brawley locations were planted in the spring of 1981, and Yuma experiment will be planted in early 1982. The Yuma location is well suited for conducting a combination water-fertility study to simulate marginal land with limited water supply and to evaluate the effects of nitrogen under different irrigation regimes. At two locations (Mesa and Yuma) bioregulators are also being evaluated in respect to improved rubber yields and tolerance to drought.

MESA, ARIZONA

GREENHOUSE PROCEDURES:

Twenty thousand guayule seedlings of three cultivars (593, N565-II, and 11591) were produced in the U. S. Water Conservation Laboratory greenhouse. Clean seeds were washed and aerated for at least six hours, followed by two hours of a 0.25% sodium hypochlorite treatment. After the seeds had dried, the treated seeds were planted into growing flats using a potting mix of two parts sphagmum peat moss and one part by volume of vermiculite and covered with a thin layer of vermiculite. Once the seedlings were 10-12 days old, they were transferred into individual plastic net pots with a volume of 70 cm^3 using the same potting mix. The transplants were fertilized three times a week with a double Hoagland's solution and mist irrigated for two to three minutes daily. The greenhouse temperature was controlled at a minimum of 25°C and a maximum of 35°C. Plants were clipped to 6 cm height before field transplanting.

FIELD PROCEDURES:

On April 7-9, the three guayule cultivars were hand transplanted at the Mesa Experiment Farm, University of Arizona, in a randomized block design. The age of cv. 593, N565-II, and 11591 transplants averaged 95, 85, and 75 days, respectively. Figure 1 shows the field layout along with irrigation, cultivar, and bioregulator treatments. Two rows were planted on raised beds (approximately 1 m on center) with a 36 cm spacing between plants along the row for a population of 54,000 plants/hectare. About one-sixth of each plot included transplants that were treated twice in the greenhouse with two types of bioregulators followed by field sprayings at two month intervals after transplanting. The bioregulator compounds were 2-diethylaminoethyl 1-3, 4-dichlorophenylether and 2-diethylaminoethyl 1-2, 4-dichlorophenyl-ether.

The transplants were immediately furrow irrigated, and then sprinkler irrigated twice-a-week for two weeks followed by once-a-week treatment for a five-week period for plant establishment. During this sprinkler irrigation period, gravimetric water contents of the potting media and soil were determined near the roots of the small transplants on additional plantings in special areas where plot border dikes were to be later constructed. Plant water potential measurements were also determined by the pressure bomb on whole plants that were cut-off at the soil surface. On a second portion of this additional area sprinkler irrigations on April 17, 21, and 24 were omitted after two sprinkler irrigations on April 10 and 14. Furrow irrigations were given on all plots on May 21 and June 18 to establish a soil moisture storage and complete this establishment period. Stand counts were made periodically and replacements were made to obtain a nearly perfect plant population. Rooting patterns were also observed on June 26.

Starting on July 1 after plant establishment, the following irrigation treatments commenced for 1981: (1) irrigate when 60% of the available soil water has been depleted; (I_2) irrigate when 80% of the available soil water has been depleted; (I_3) irrigate when 100% of the available soil water has been depleted; (I_4) irrigate when 100% of the available soil water has bee depleted plus a two weeks delay; (I_5) irrigate when 100% of the available soil water has been depleted plus a four weeks delay; and (I_6) irrigate three times per year. The 0-120 cm soil depth was used to schedule irrigations and calculate soil water depletions. Volumetric water contents were determined by neutron moisture meters with 36 neutron access tubes located in replicates 2 and 3 on all three cultivars, and six irrigation treatment to a 3 m soil depth. On the medium water holding capacity Laveen loam soil field capacity has consistently been estimated at 25.7% by volume, whereas a wilting point of 8.6% was estimated from reoccurring lower limits of water uptake on older guayule plants.

Water applications at each irrigation were measured by a propeller-type water meter, and aluminum gated-pipe was used in delivering water to the individual plots surrounded by earth border dikes covered with a plastic film. Meteorological factors affecting ET were monitored beginning on August 17 by portable stations equipped with CR21 microloggers. Weather data were determined on the I_2 irrigation treatment for guayule and on an adjacent alfalfa field for a reference crop. On the guayule, wind speed was determined at the 2 m height; net radiation, air temperature, and relative humidity at the 1.5 m height; net radiation at 1/2 the plant height; and soil temperature at 1 cm depth below the soil surface. On the alfalfa, solar radiation and wind speed were determined at the 2 m height; net radiation, air temperature, and relative humidity at the 1.5 m height; and soil temperature at 1 cm below the soil surface. Starting in October, remotely-sensed infrared radiometer measurements were made to monitor foliage temperature and estimate stress in guayule. Leaf area, plant weights, and rubber percentages were also being sampled at least five time per year beginning in August 1981. Two plants per were are selected for each harvest date, as described in Figure 2, for a total of 144 whole plants with roots. The final harvest date will be in late 1989 with at least 36 plants to be harvested per cultivar and irrigation plot.

RESULTS AND DISCUSSION:

Table 1 shows that 467 mm (18.4 inches) of water was applied during the first three months of transplant establishment. Maximum and minimum air temperatures in the first two weeks averaged 30 and 12°C, respectively. B mid-June, plant losses were less than 5% for the three cultivars (Table 2) Figures 3 and 4 indicate that water contents in the potting mix were lower than the surrounding soil and that the potting mix became drier sooner tha the soil without the frequent-light sprinkler irrigations. Careful water management and plant observations were required to maximize plant survival since plant roots took at least three weeks to extend outside of the potting mix and develop in the soil. Well-watered guayule plants had water potentials below a -10 bars (Figure 5) and plants began to wilt at about 14 bars, whereas the nonirrigated plants had either died or were severely stressed at -18 bars under these field conditions.

The amounts of water applied on the six different irrigation treatments after the establishment period (before July 1) are listed in Table 3. Water applications ranged from 931 mm (36.7 inches) with seven irrigations on the I_1 treatment to 458 mm (18.0 inches) with three irrigations on the I_6 treatment. The number and amount of irrigations on the I_4 and I_5 treatments were the same, although the timing of irrigation was different. Mean plant heights from transplanting to the end of 1981 for the three cultivars produced under the six irrigation treatments are shown in Figures 6-11. Plant heights decreased consistently with reduced irrigation amounts for the I_1 through I_3 treatments; on the other hand, heights varied order of plant heights between cultivars is 11591 taller than N565-II followed by 593. By December 31, the maximum plant height was over 4 cm (16 inches) and the crop canopy covered the entire soil surface on the I_1 and I_2 irrigation treatments.

Changes in the soil water content averaged for the three cultivars versus time showed that irrigations after July 1 were actually given when 74%, 77%, 82%, 89%, 80%, and 80% of the available soil water was depleted in the 0-120 cm soil depth for the six irrigation treatments, respectively (Figures 12-17). The reduced growth and shedding of plant leaves on the I_5 and I_6 treatments possibly limited the ability of the guayule plants to extract water below the 80% level. Figures 18-23 present soil water content profiles through a 3 m soil depth and estimated plant rooting depths for selected dates on the six irrigation treatments. By the end of plant establishment (July 1), plant roots had penetrated to a depth of more than 60 cm (2 feet) which was verified by the presence of roots in the soil profile from excavations made on June 26. Water content profiles thereafter suggest that plant rooting reached depths of 140 cm (4.6 feet) by the end of the first year regardless of the amount of water applied or irrigation schedule.

Average soil water depletion rates for the three cultivars and six irrigations are shown in Figures 24-29. The estimated seasonal water used for the initial growth from May through December for each irrigation treatment in order of decreasing water applications was 955, 780, 705, 600, 605, 605 mm, respectively. These depletion rates were consistent with plant height measurements which showed major differences in growth on the three wet treatments and little difference in growth on the three day treatments. In comparing the seasonal soil water depletion with the total water applied during this same period of time (May-December), water application efficiencies ranged from 80%, 74%, 76%, 73%, 73%, 83% for the six treatments, respectively. Higher application efficiences can be expected in the future since adequately stored moisture was still present in the soil profile for initial plant water use in 1982. A trend of increased soil water depletion for the cv. 11591 over N565-II over 593 was demonstrated but a difference in water use between cultivars was not significant. Also, soil water depletion rates tended to decrease in late July and early August for all treatments. Possible explantions for this dip in the soil water depletion curve are decreased flowering or seed production and/or reduced leaf area (dropping of plant leaves) during high temperature periods.

Plant temperatures as measured by the infrared radiometer late in 1981 showed that relief from water stress followed from the onset and duration of an irrigation or rainfall event (Figures 30 and 31). Since all treatments were irrigated on November 10 to insure an adequate supply of stored moisture for the dormancy period during the first year, plant-air temperature differences were not drastically altered by the irrigation treatments. However, the cv. 593 tended to have higher plant temperatures than the other two cultivars. Also, the cv. 593 treated with bioregulator B (2diethylammnoethyl 1-2, 4-dichlorophenylether) exhibited an even hotter plant temperature than the bioregulator A (2-diethylaminoethyl 1-3, 4-dichlorophenylether) or untreated plants on the drier I_4, I_5, and I_6 irrigation treatments (data not shown).

Meteorological measurements and the development of crop coefficients for several ET prediction equations are still to be analyzed. Plant samples from all three cultivars and six irrigations were collected in late August and November for leaf area and rubber yields. These have been processed, but the rubber concentrations have yet to be determined.

BRAWLEY, CALIFORNIA

GREENHOUSE PROCEDURES:

Six thousand seedlings of cv. 11591 and 500 of cv. 593 were produced in a similar manner at the U. S. Water Conservation Laboratory greenhouse as described for the Mesa, Arizona experiment. However, when the plants were about four weeks old, they were transferred to the Brawley greenhouse for the last two months of seedling growth. Again, the transplants were clipped one week before transplanting to a height of 6 cm.

FIELD PROCEDURES:

On March 24, seedlings of cv. 11591 were transplanted on 19 rows, as shown in Figure 32. Planting was on 2-row raised beds (approximately 1 m on center) with a 36 cm spacing between plants along the row for a population of 54,000 plants/hectare. About one week later, 2 rows of cv. 593 were planted on the east side of the original transplants. The furrow irrigati n method was utilized for plant establishment.

A large lysimeter 3 m x 3 m and 1.5 m deep located in the center of the field plot was used to determine daily evapotranspiration (ET) rates durin the development of the guayule plant. One neutron access tube was placed in the lysimeter, and two tubes per irrigation treatment were placed in the adjacent plots. The planned irrigation treatments consisted of a medium irrigation treatment in and around the lysimeter, while wetter and drier treatments were to be maintained away from the lysimeter. Plant height measurements were made monthly, and irrigation water applications were measured onto the lysimeter and adjacent plots. Meteorological observatio s included daily maximum and minimum air temperatures, average relative humidity, total wind movement, Class A pan evaporation, precipitation, tot l solar radiation, and net radiation. These measurements were recorded abou

0900 PST at a Weather Bureau station with Bermuda grass cover located at the Imperial Valley Experiment Station and about 400 yards from the guayule lysimeter plots.

RESULTS AND DISCUSSION:

Better than 98% survival of guayule transplants was achieved at Brawley, California, using furrow irrigation. On the heavy-textured soil, plant growth was better in the lysimeter than in the adjacent irrigation plots. On June 12, the last uniform irrigation was applied on the lysimeter and buffering plots based on plans to begin differential irrigations thereafter. However, irreversible damage occurred on the plants surrounding the lysimeter on June 12-13 because the irrigation water was allowed to stand for over 12 hours. High air temperatures of 42° and 43°C for the 2 days also could have contributed to the problem. Plant losses were the greatest in the low-lying areas of the field where over 75% of the plants died in a very short period of time. Waterlogging or oxygen deficiency based on visual observations and the elimination of other causes remains the most probable reason for the catastrophe. Due to the better drainage characteristics in the lysimeter, none of the plants showed damage in the lysimeter.

Operation of the lysimeter continued until the entire plot plus the lysimeter could be replanted in the fall. Table 4 shows that 12 irrigations totaling 1514 mm of water was applied on the lysimeter from March 24 to October 22. During the same period of time, the seasonal ET was measured at 1490 mm (58.7 in.) as shown in Figure 33. The high ET rates which went above 12 mm/day in July were the result in part of scheduling irrigations with minimal plant water stress and the lysimeter not being environmentally buffered for the last 4 months of the 7 month period. Crop coefficients comparing the measured ET to the potential ET for the reference Bermuda crop as calculated from various meteorological equations have not been fully determined; however, the seasonal pan coefficient was 0.64. Also, whole plant samples were obtained before replanting of the lysimeter on October 22, but rubber and resin analyses have not been completed at this time.

SUMMARY AND CONCLUSIONS:

Better than 95% transplant survival was obtained at two locations with medium-textured (Mesa, Arizona) and heavy-textured (Brawley, California) soils. The key to successful plant establishment was the careful control of water applications either through sprinkler or furrow irrigation with some or all of the three cultivars (11591, 593, N 565-II).

Drought-tolerant guayule plants depleted water in the first season of growth in relationship to the availability of soil water and environmental demands. Where water applications were high, water use was high; whereas with low water application rates, soil water depletion was low. At Mesa, the seasonal water depletions for six irrigation treatments in decreasing order of water applications was 955, 780, 700, 600, 600, and 600 mm from May through December. Plant growth decreased significantly among the three wetter treatments, while little difference was noted on the three drier treatments.

Soil water content profiles indicated that guayule roots extracted water to depths greater than 140 cm by the end of the first year regardless of the amount of water applied or irrigation schedule.

At Brawley, seasonal evapotranspiration based on lysimetric measurements was 1490 mm over the March through October period with minimal water stress exhibited by the plant. Young guayule plants were found to be extremely sensitive to waterlogging under high temperature conditions where irreversible damage can occur.

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PERSONNEL: D. A. Bucks, F. S. Nakayama, W. L. Ehrler, O. F. French, W. L. Alexander, W. W. Legard, B. A. Rasnick, J. M. Martinez (U. S. Water Conservation Laboratory); C. K. Arterberry (Imperial Valley Conservation Research Center).

Table 1. Water application amounts applied during the establishment of guayule at Mesa, Arizona, 1981.

Irrigation Date	Irrigation Method	Water Applied
		mm
Apr 7-9	Furrow	108
Apr 10	Sprinkler	19
Apr 14	Sprinkler	11
Apr 17	Sprinkler	18
Apr 21	Sprinkler	18
Apr 24	Sprinkler	15
May 04	Sprinkler	19
May 12	Sprinkler	18
May 15	Sprinkler	16
May 21	Furrow	105
Jun 18	Furrow	112

Total water applied for plant establishment 467 mm (18.4 inches)

Table 2. Plants replaced by mid-June after initial transplanting on April 7-9, 1981.

Cultivar	Average Plant Age at Transplanting	Plants Replanted*	Percent Replanted
	Days	Number	%
593	75	238	6.9
N 565-II	95	139	4.0
11591	85	152	4.3
All Three	85	529	5.1

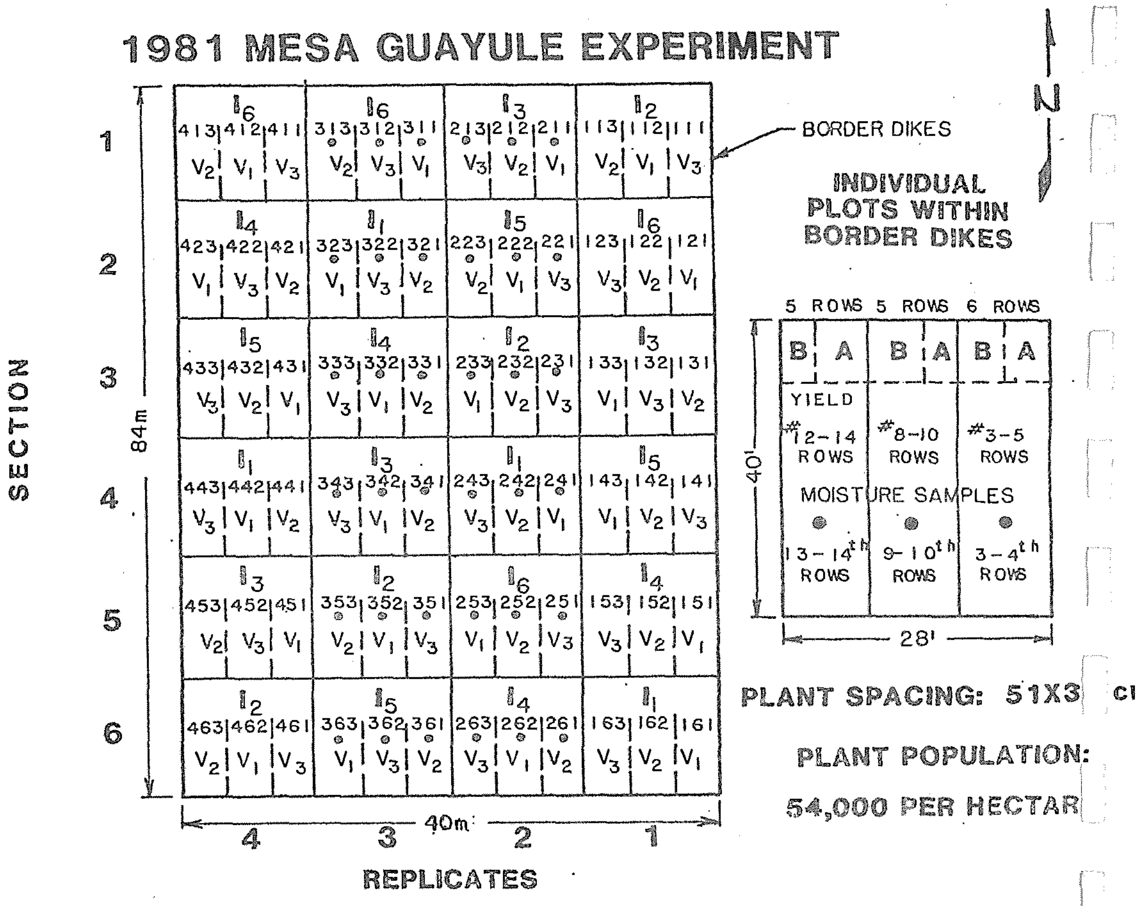
* Seedlings had either died or were physically damaged during transplanting, cultivation, etc., from the period of April 7 to June 4.

Table 3. Water application amounts applied using the furrow method on the six different irrigation treatments after establishment at Mesa, Arizona, 1981.

Irrigation Treatment					
Irrig. Date	Irrig. Amt.	Irrig. Date	Irrig. Amt.	Irrig. Date	Irrig. Amt.
I_1		I_2		I_3	
Jul 10	137	Jul 14	136	Jul 22	127
Jul 07	126	Aug 04	135	Aug 20	138
Aug 15	136	Aug 31	132	Sep 16	131
Aug 31	132	Sep 23	121	Oct 16	131
Sep 16	131	Oct 16	131	Nov 10	135
Oct 08	134	Nov 10	135		
Nov 10	135				
Total	931 mm (36.7 in)		700 mm (31.1 in.)		662 mm (26.1 in.)
I_4		I_5		I_6	
Jul 27	126	Aug 04	135	Aug 15	161
Aug 27	138	Aug 31	154	Sep 23	162
Sep 23	161	Oct 08	134	Nov 10	135
Nov 10	135	Nov 10	135		
Total	560 mm (22.0 in.)		558 mm (22.0 in.)		458 mm (18.0 in.)

Table 4. Water application amounts applied using the furrow method on the lysimeter.

Irrigation Date	Irrigation Amount
	mm
Mar 24	182
Apr 01	82
Apr 09	80
Apr 29	76
May 20	86
Jun 12	126
Jul 08	178
Jul 30	155
Aug 19	142
Sep 02	137
Sep 17	143
Sep 23	127
Total Water Applied	1514 (59.6 in.)



LEGEND:

IRRIGATION TREATMENTS

I_1 =60% SMD* -BLACK
I_2 =80% SMD-BLUE
I_3 =100% SMD-GREEN
I_4 =100% SMD PLUS 2 WEEKS-RED
I_5 =100% SMD PLUS 4 WEEKS-WHITE
I_6 =THREE IRRIG. PER YEAR-YELLOW

CULTIVARS

V_1 =593
V_2 =N565-II
V_3 =11591

BIOREGULATORS

A=2-DIETHYLAMINOETHYL 1-3,4-DICHLOROPHENYLETHER
B=2-DIETHYLAMINOETHYL 1-2, 4-DICHLOROPHENYLETHER

* SOIL MOISTURE DEPLETION IN A 0 - 120 cm SOIL DEPTH

● LOCATION OF 36 NEUTRON ACCESS TUBES TO A 300 cm SOIL DEPTH

Figure 1. Plot diagram, irrigation treatments, cultivars, and bioregulators used at Mesa, Arizona, 1981.

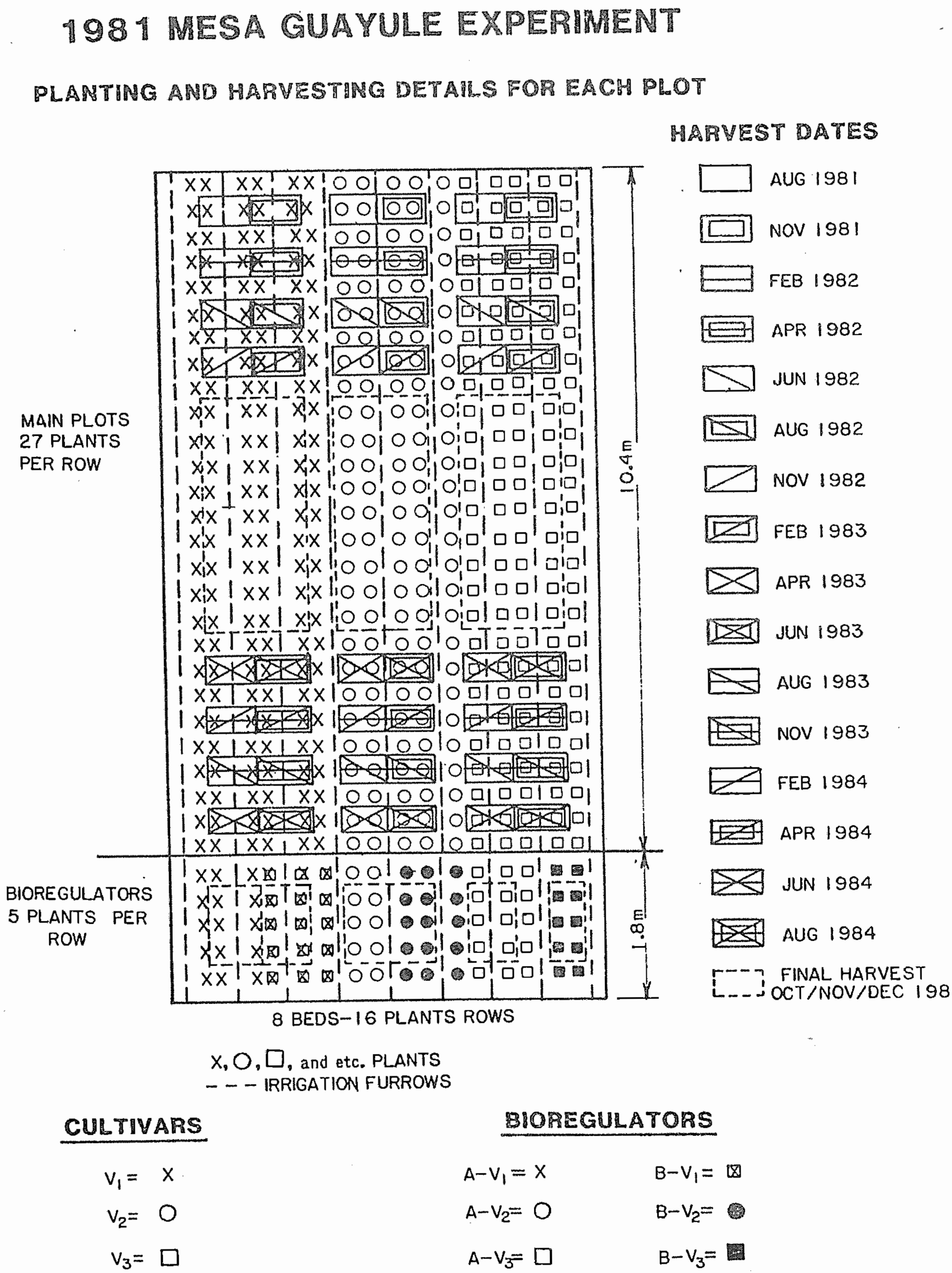


Figure 2. Details of planting and periodic harvests at Mesa, Arizona, 1981.

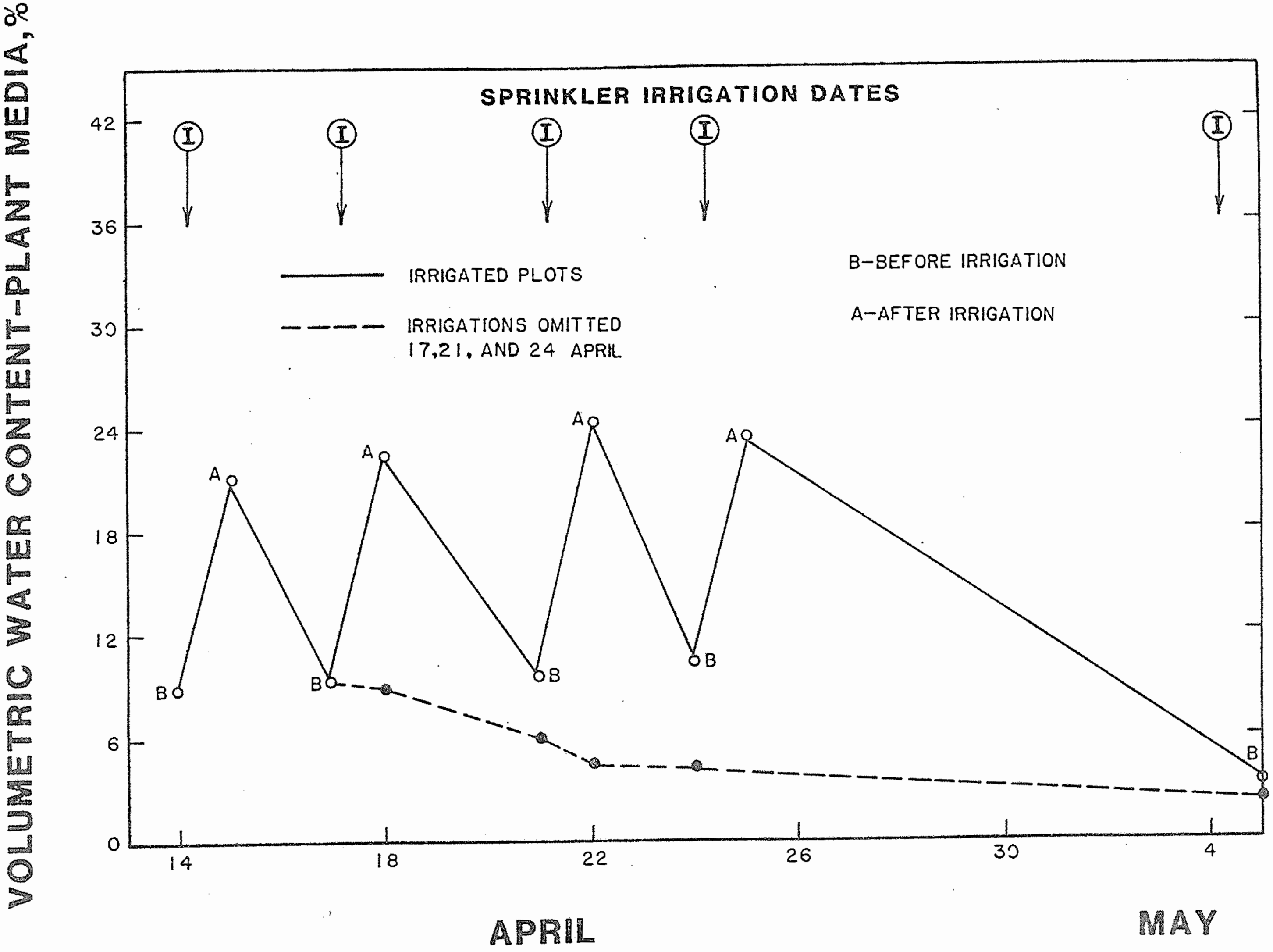


Figure 3. Volumetric water contents of the potting media near the roots of small transplants during the establishment period at Mesa, Arizona, 1981

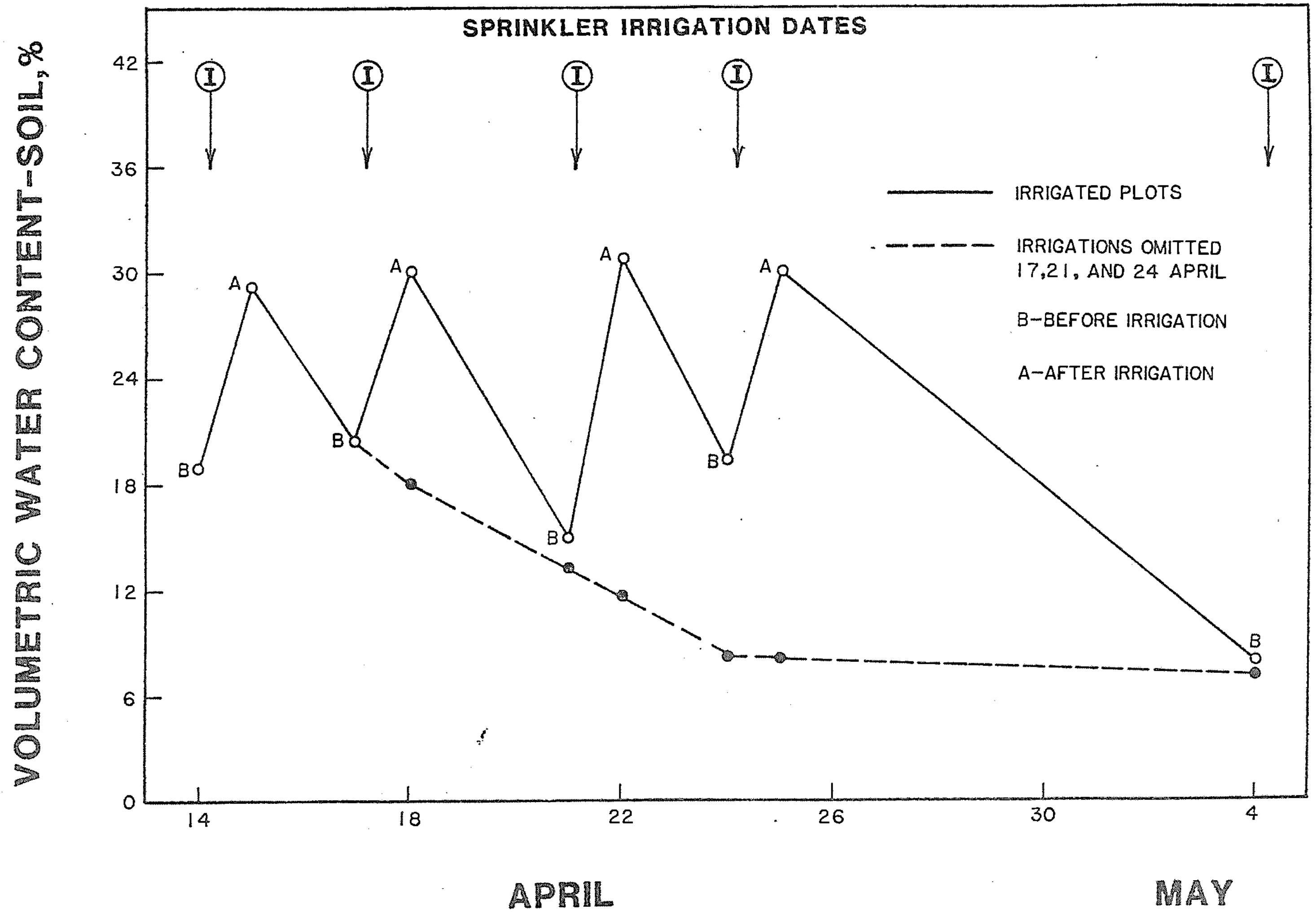


Figure 4. Volumetric water content of the soil near the roots of samll transplants during the establishment period at Mesa, Arizona, 1981.

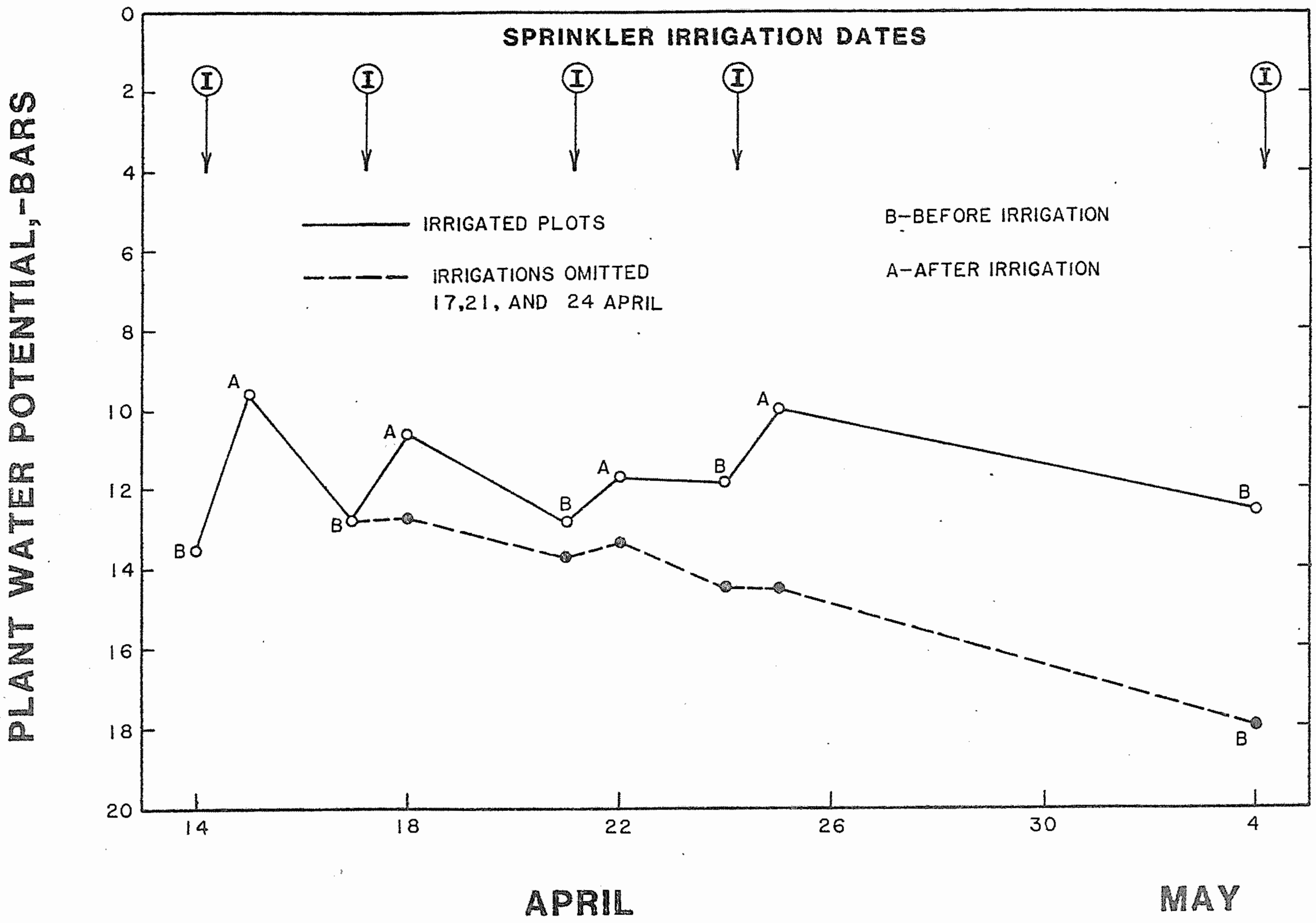


Figure 5. Plant water potential measurements for small transplants during the establishment period at Mesa, Arizona, 1981.

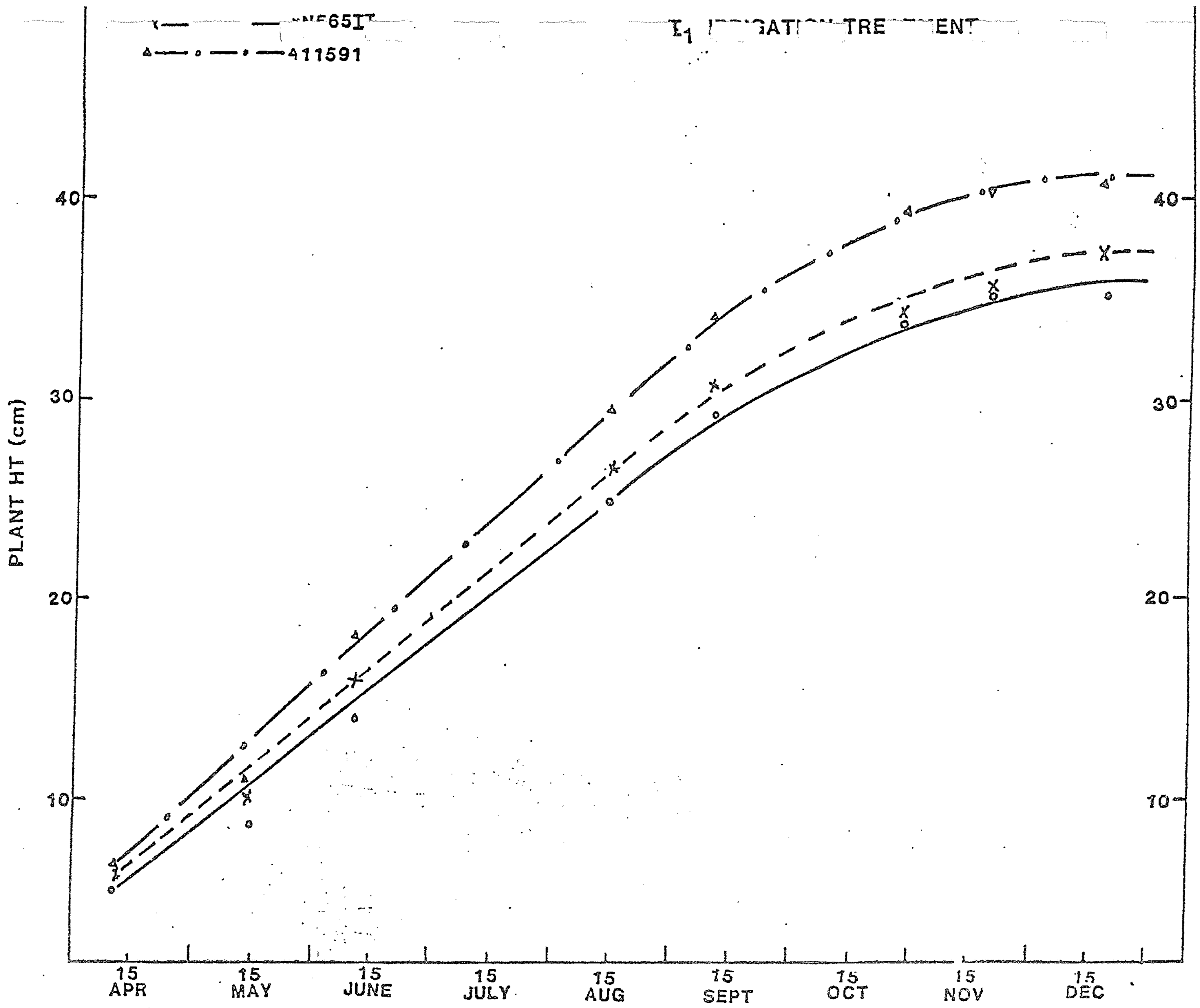
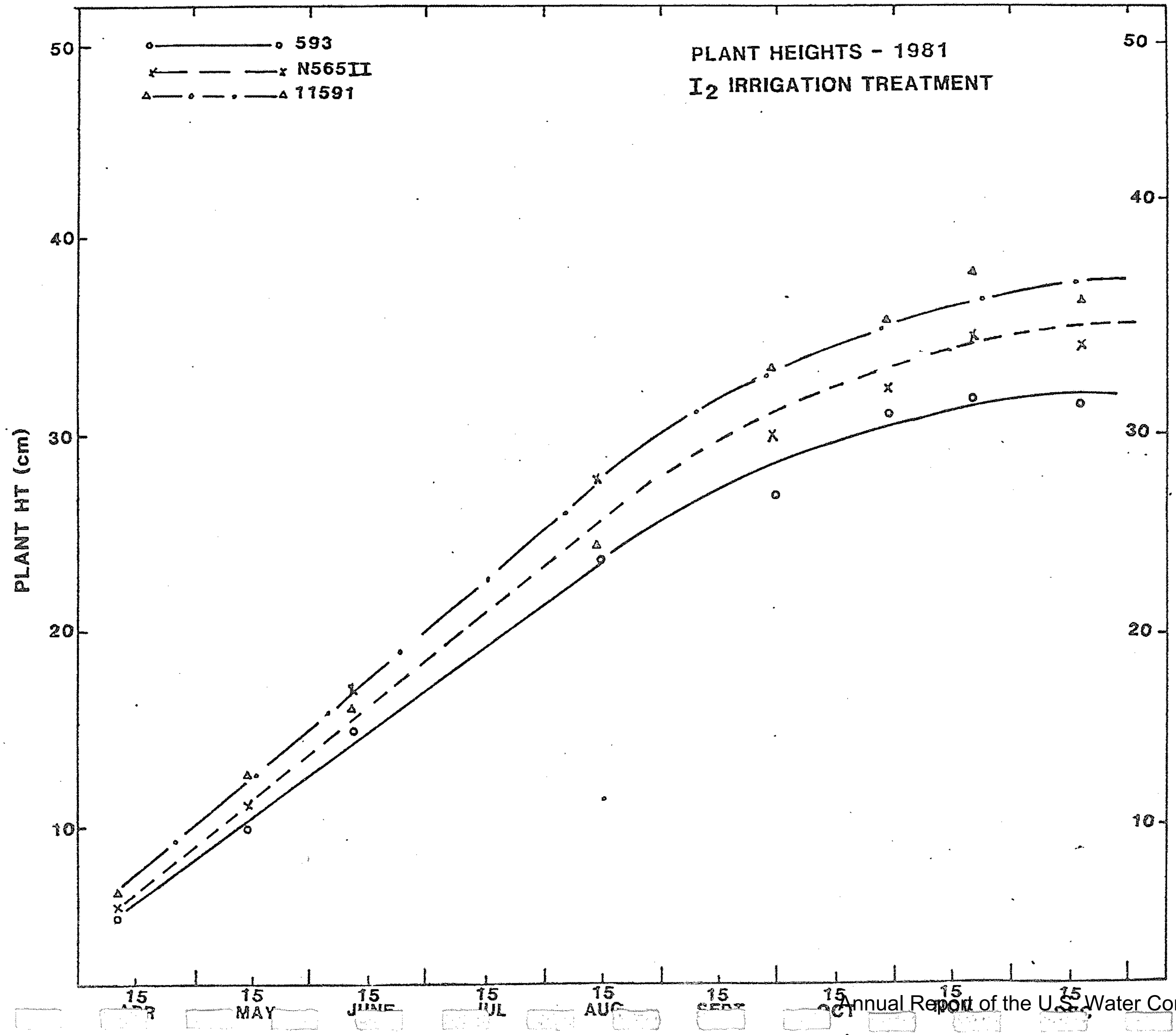


Figure 6. Average plant heights for three cultivars produced under the I_1 irrigation treatment at Mesa, Arizona, 1981.


593
N565II
11591
PLANT HEIGHTS - 1981
I_2 IRRIGATION TREATMENT
PLANT HT (cm)
50
40
30
20
10
15
MAY
JUNE
JUL
AUG
OCT

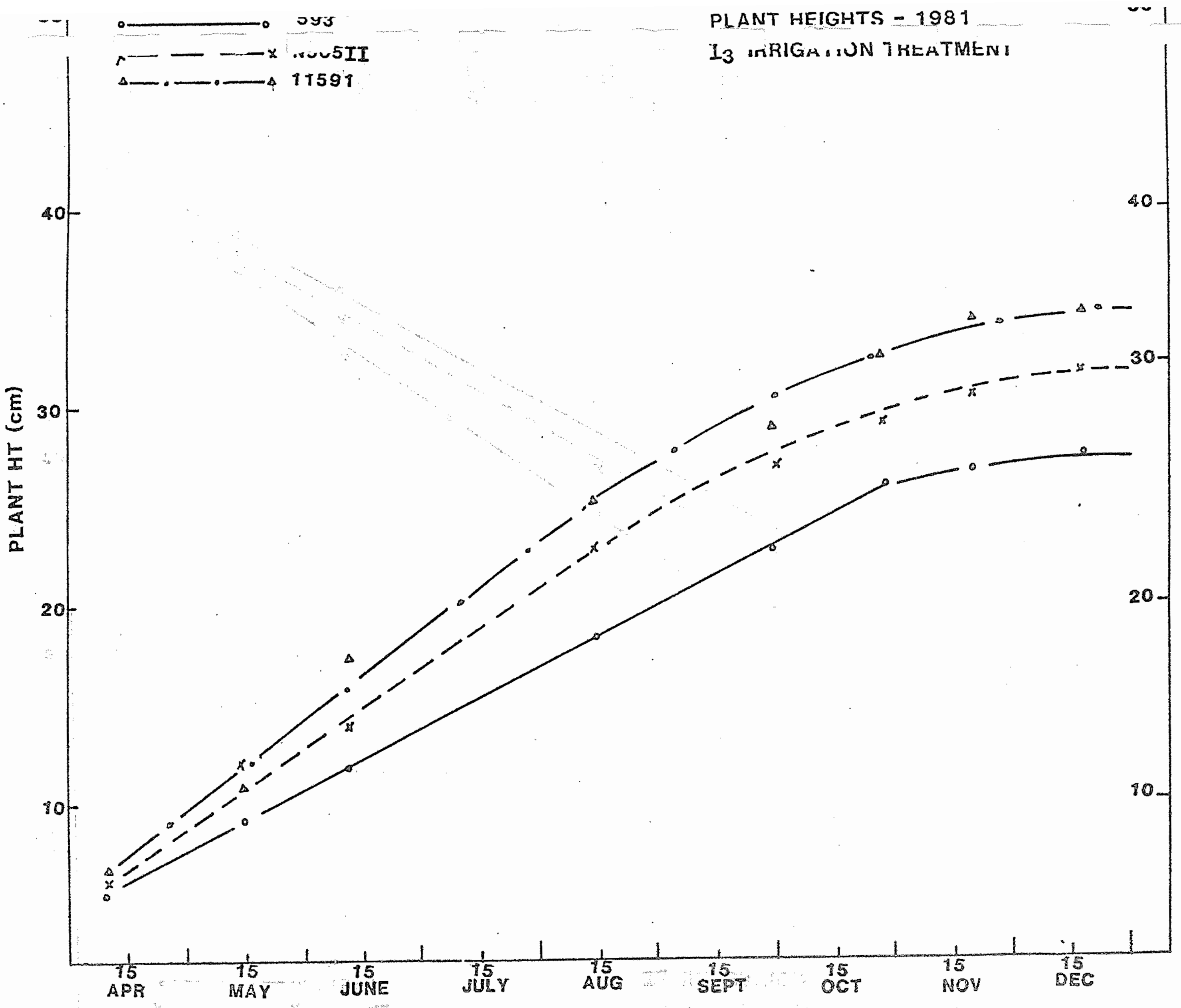


Figure 8. Average plant heights for the three cultivars produced under the I_3 irrigation treatment at Mesa, Arizona, 1981.

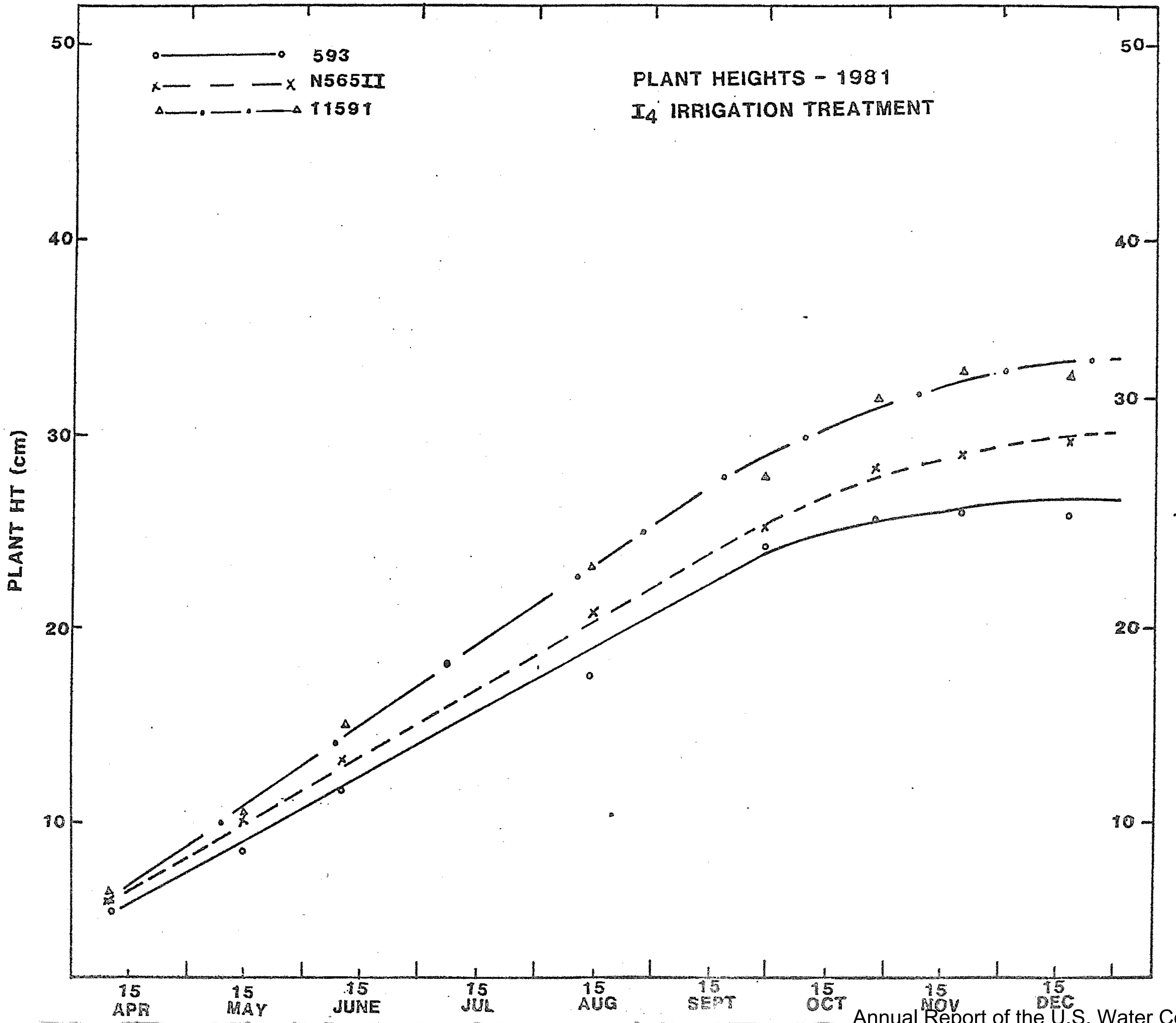


Figure 9. Average plant heights for the three cultivars produced under the I_4 irrigation

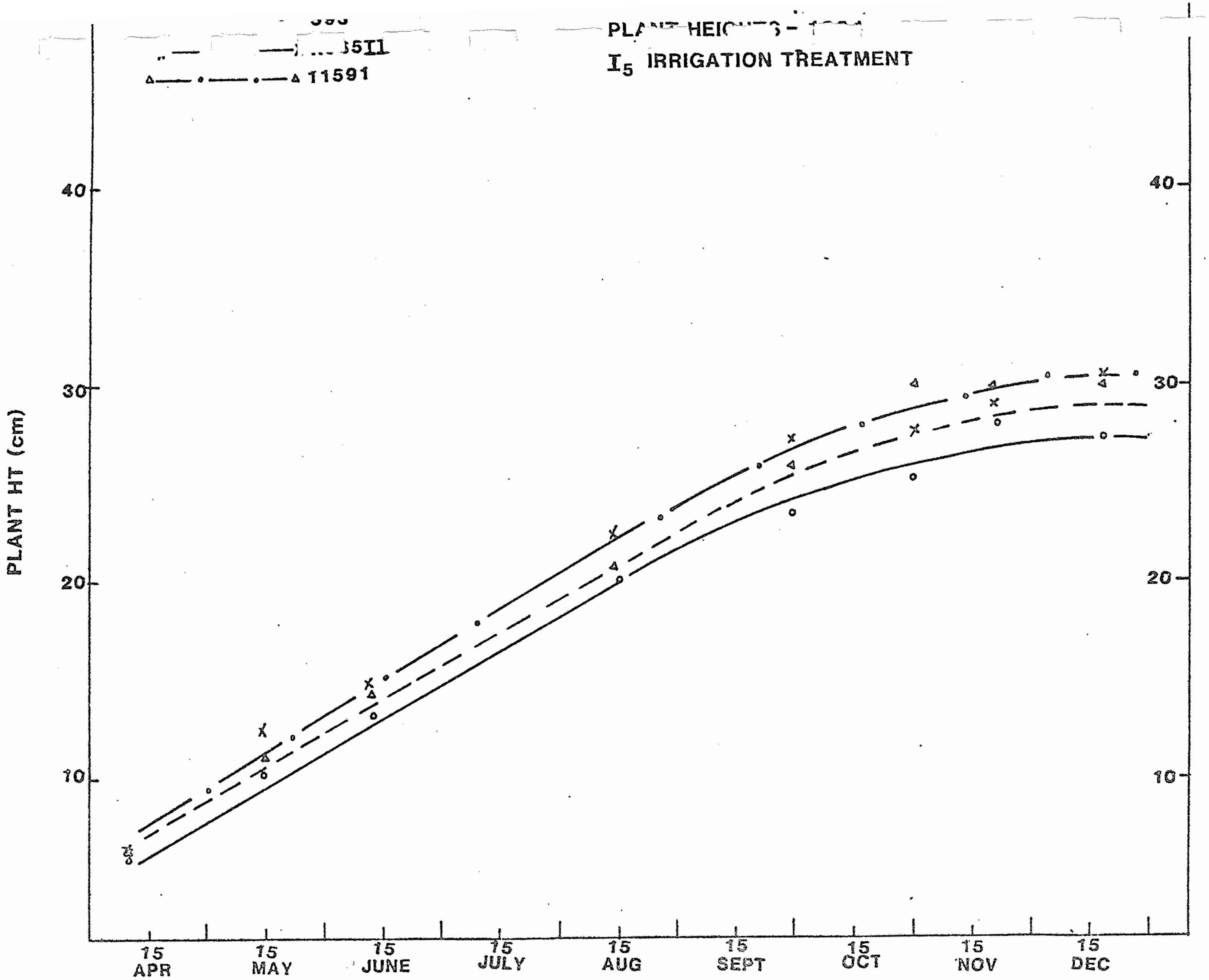
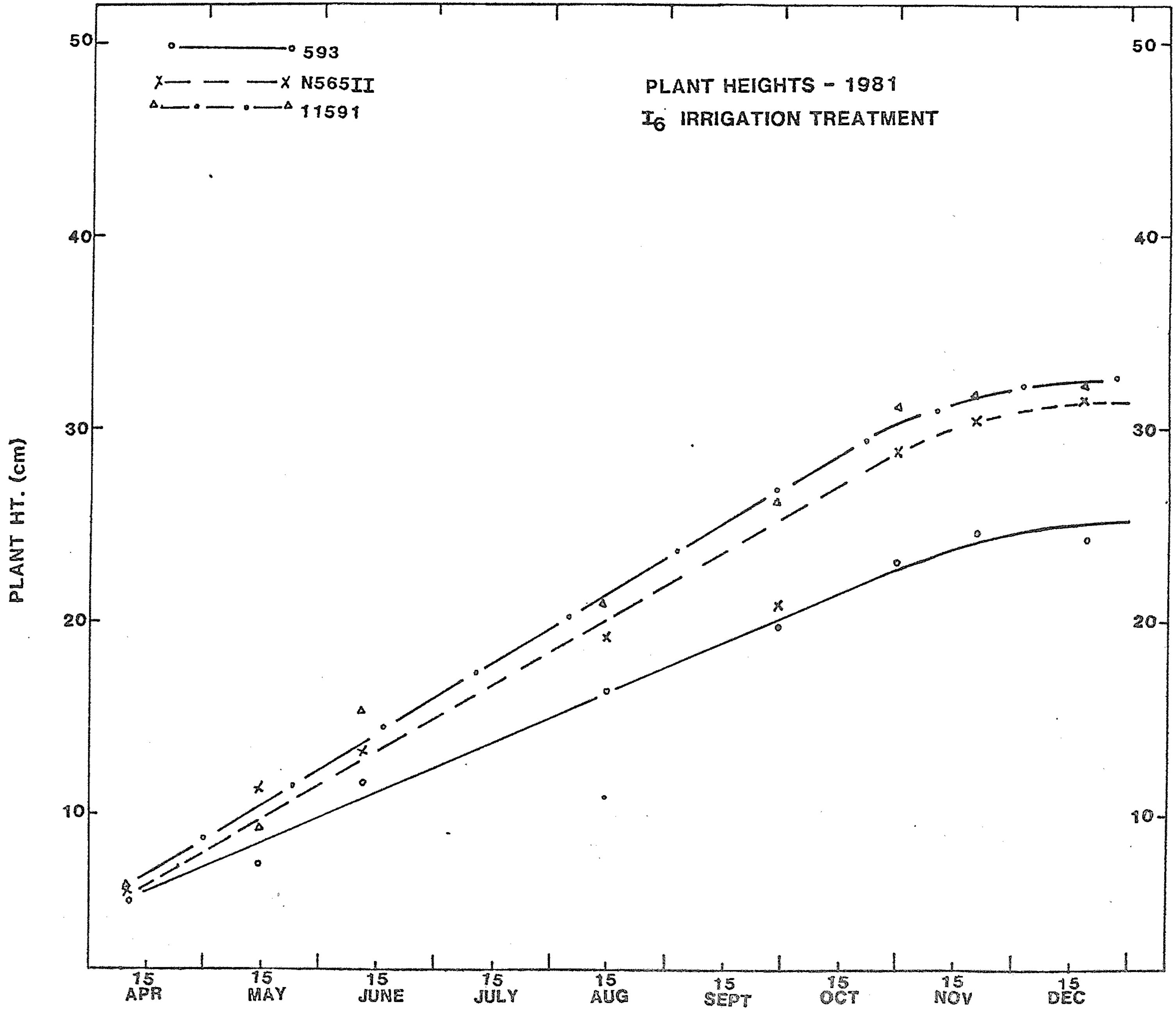


Figure 10. Average plant heights for the three cultivars produced under the I_5 irrigation treatment at Mesa, Arizona, 1981.



[illegible]igur[illegible] 1. [illegible]rag[illegible] ant[illegible]ight[illegible]or [illegible] thr[illegible] ult[illegible]s [illegible]uce[illegible]der[illegible] I_6 [illegible]iga[illegible]
treatment at Mesa, Arizona, 1981.

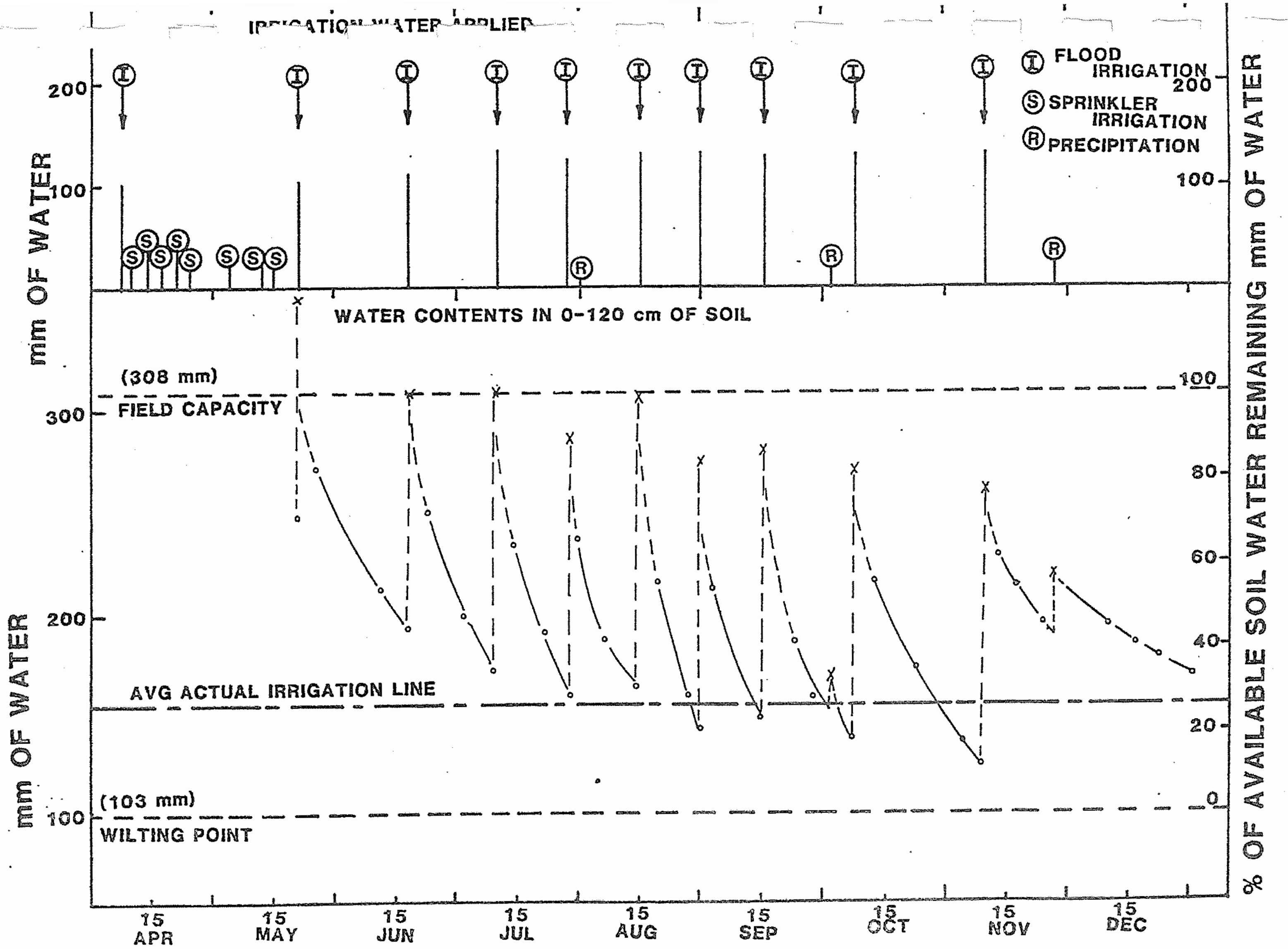


Figure 12. Irrigation water applied and average soil water contents for the I_1 irrigation treatment at Mesa, Arizona, 1981. (Seven irrigations were applied after July 1 when 74% of the available soil water was depleted in the 0-120 cm depth).

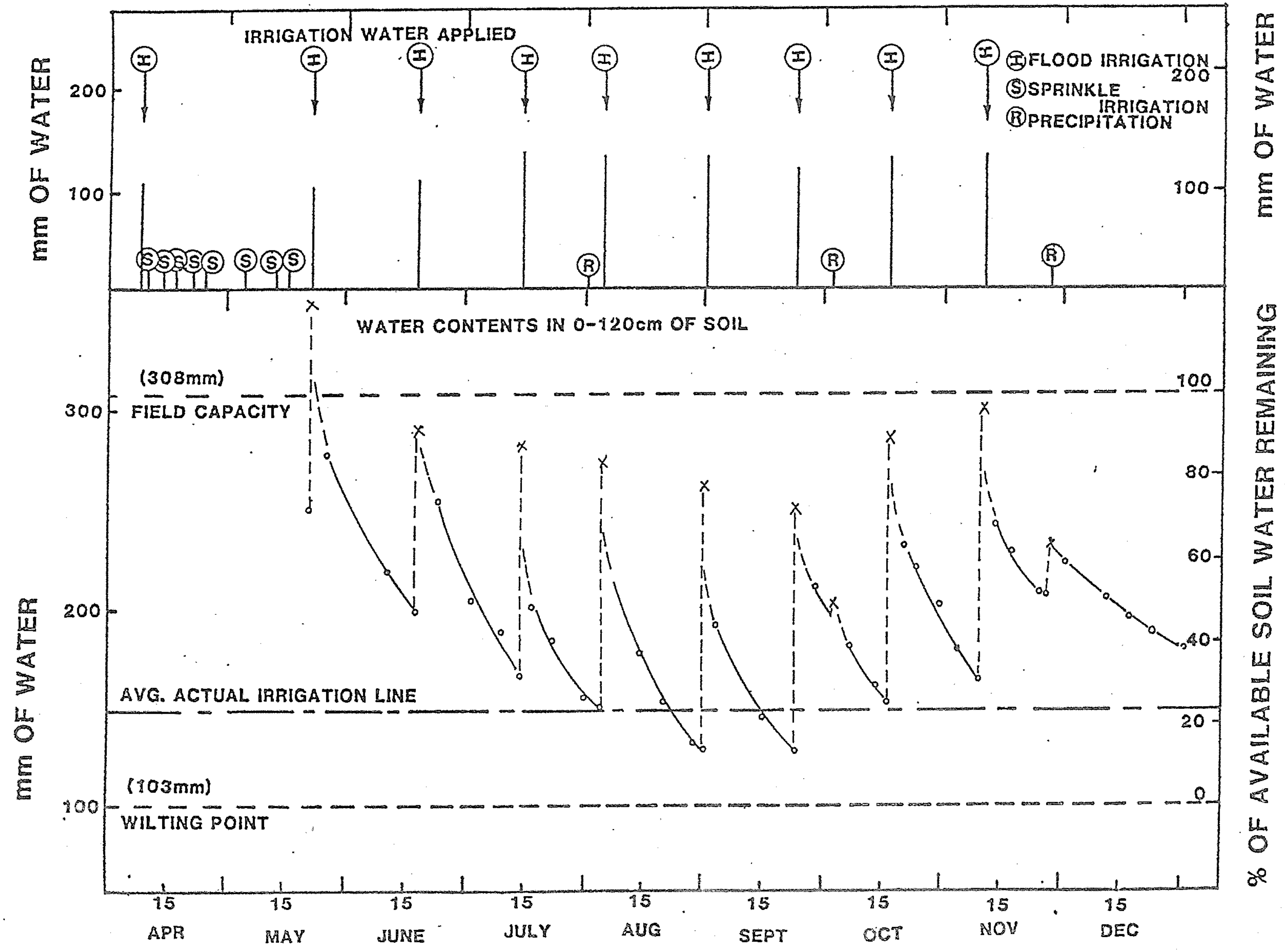


Figure 13. Irrigation water applied and average soil water contents for the I irrigation treatment ... Mesa, Arizona, 19... (... irrigations were applied after ...y ... when ... of the available soil water was depleted in the 0-120 cm depth).

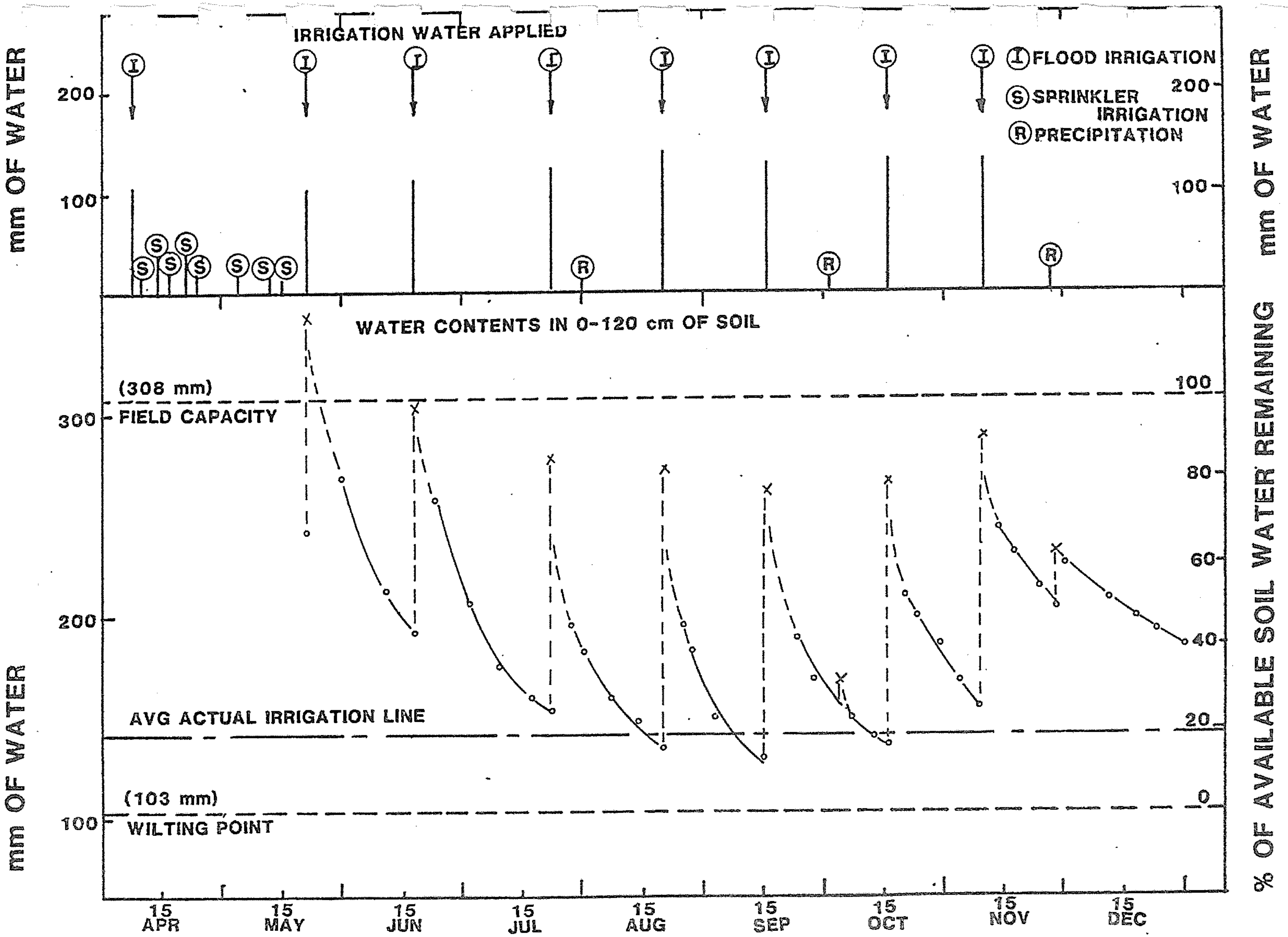


Figure 14. Irrigation water applied and average soil water contents for the I_3 irrigation treatment at Mesa, Arizona, 1981. (Five irrigations were applied after July 1 when 82% of the available soil water was depleted in the 0-120 cm depth).

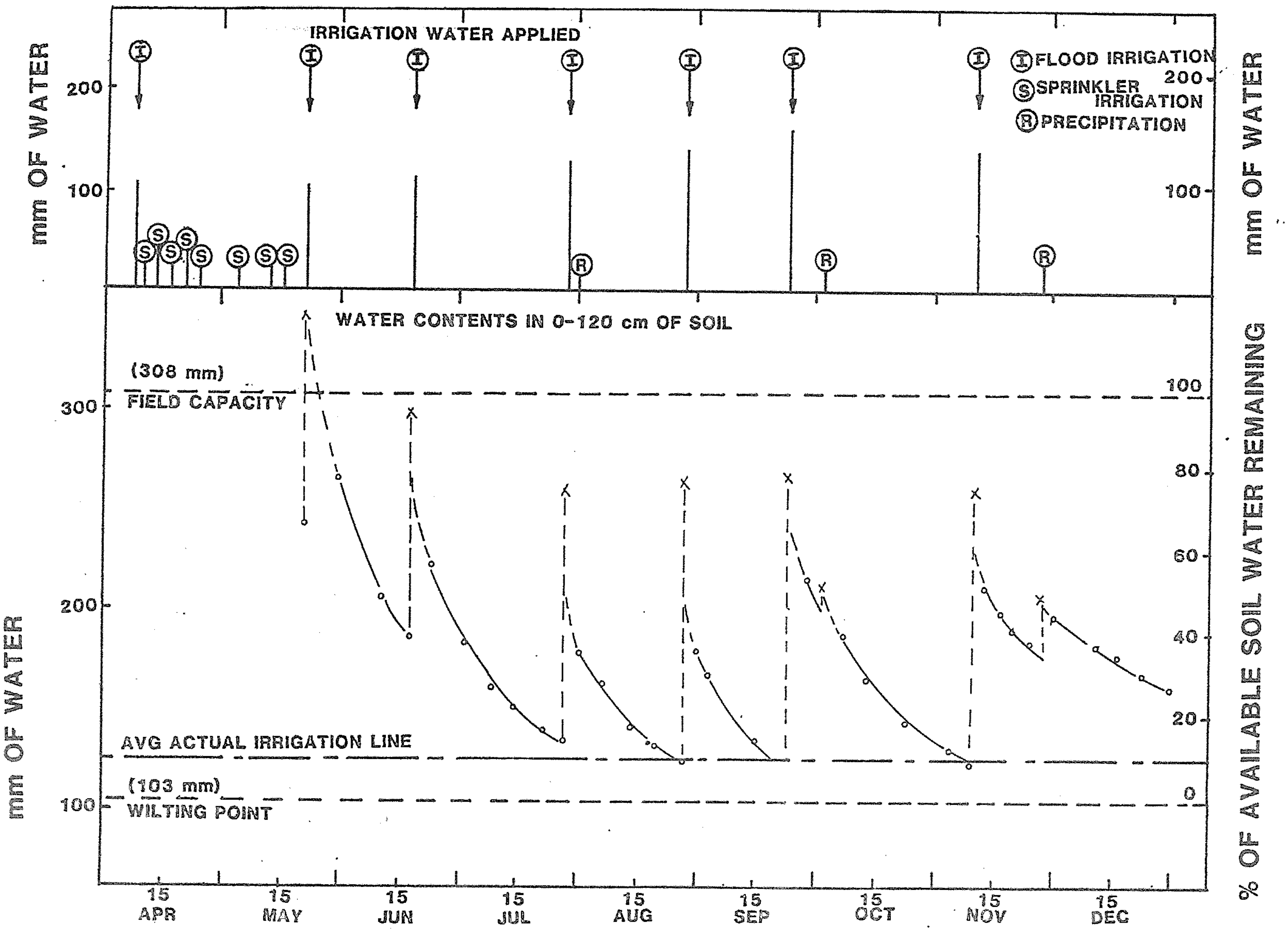


Figure 15. Irrigation water applied and average water contents for the I[illegible] irrigation treatment [illegible] Mesa [illegible] riz[illegible] 19[illegible] (F[illegible] ir[illegible] tio[illegible] ere[illegible] lie[illegible] ter[illegible] ly [illegible] en [illegible] of [illegible] available soil water was depleted in the 0-120 cm depth).

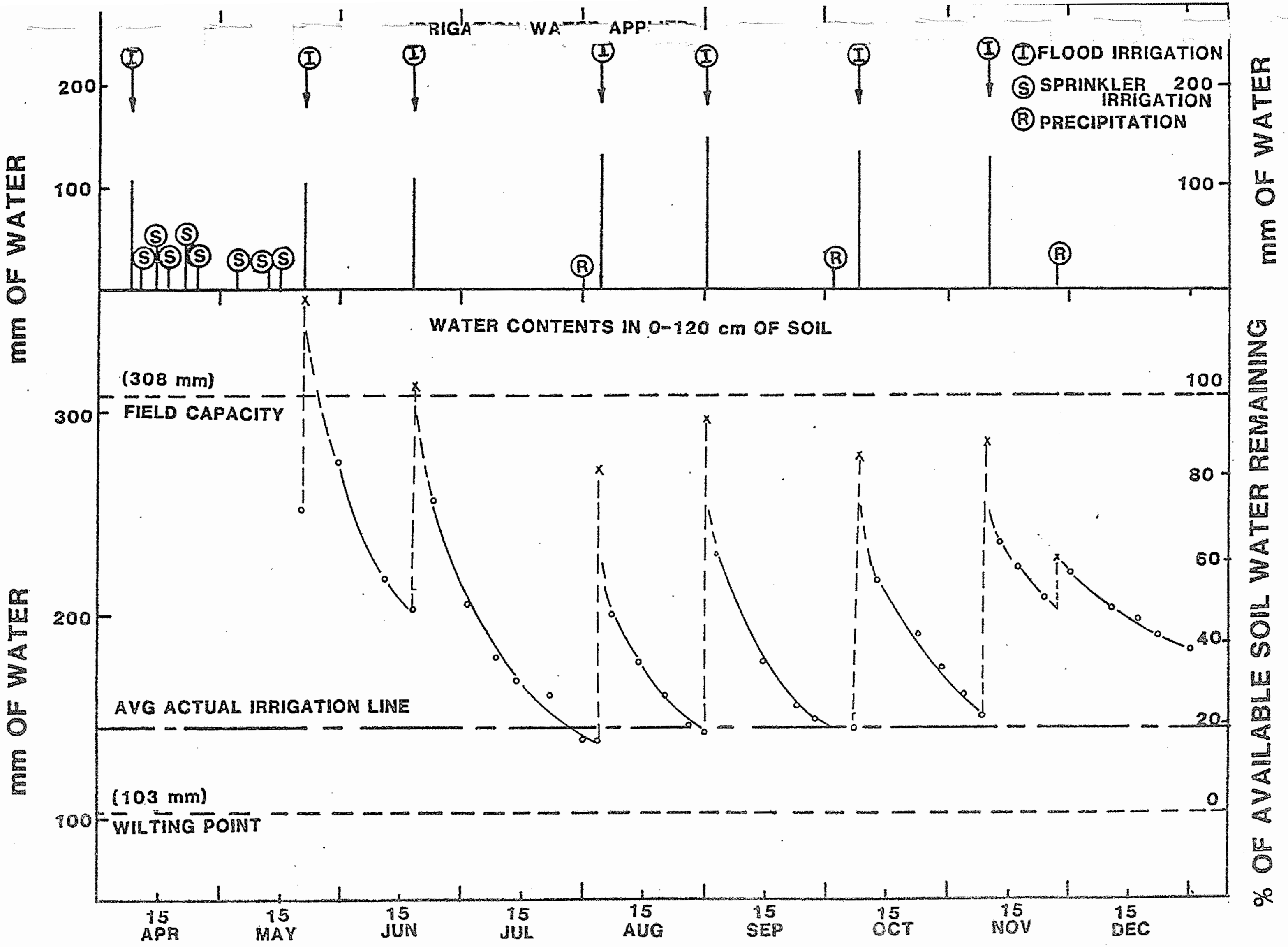


Figure 16. Irrigation water applied and average water contents for the I_5 irrigation treatment at Mesa, Arizona, 1981. (Four irrigations were applied after July 1 when 80% of the available soil water depleted in the 0-120 cm depth).

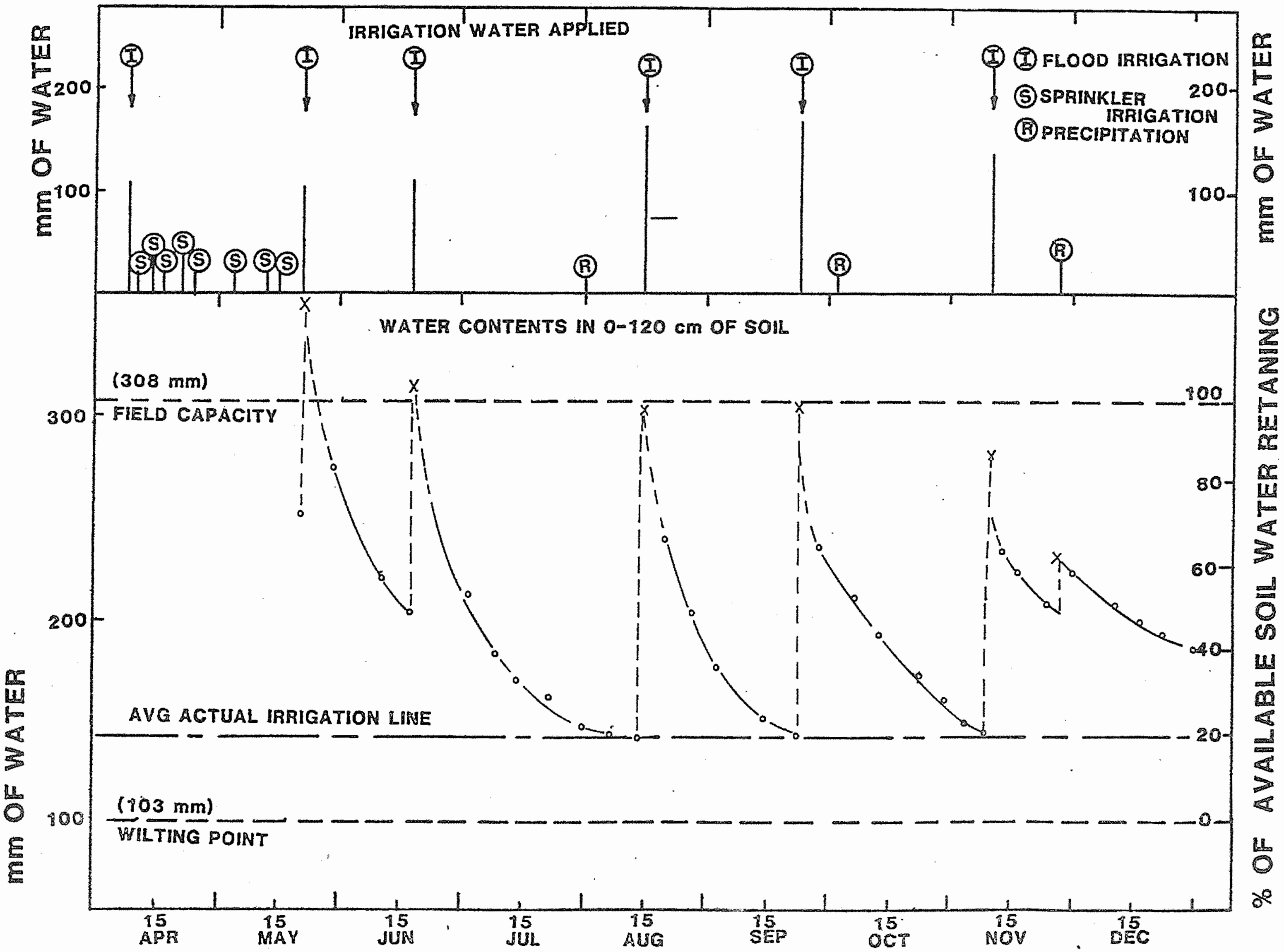


Figure 17. Irrigation water applied and average soil water contents for the I_6 irrigation treatment at Mesa, Arizona, 1981. (Three irrigations were applied after July 1 when 80% of the available soil water was depleted in the 0-120 cm depth).

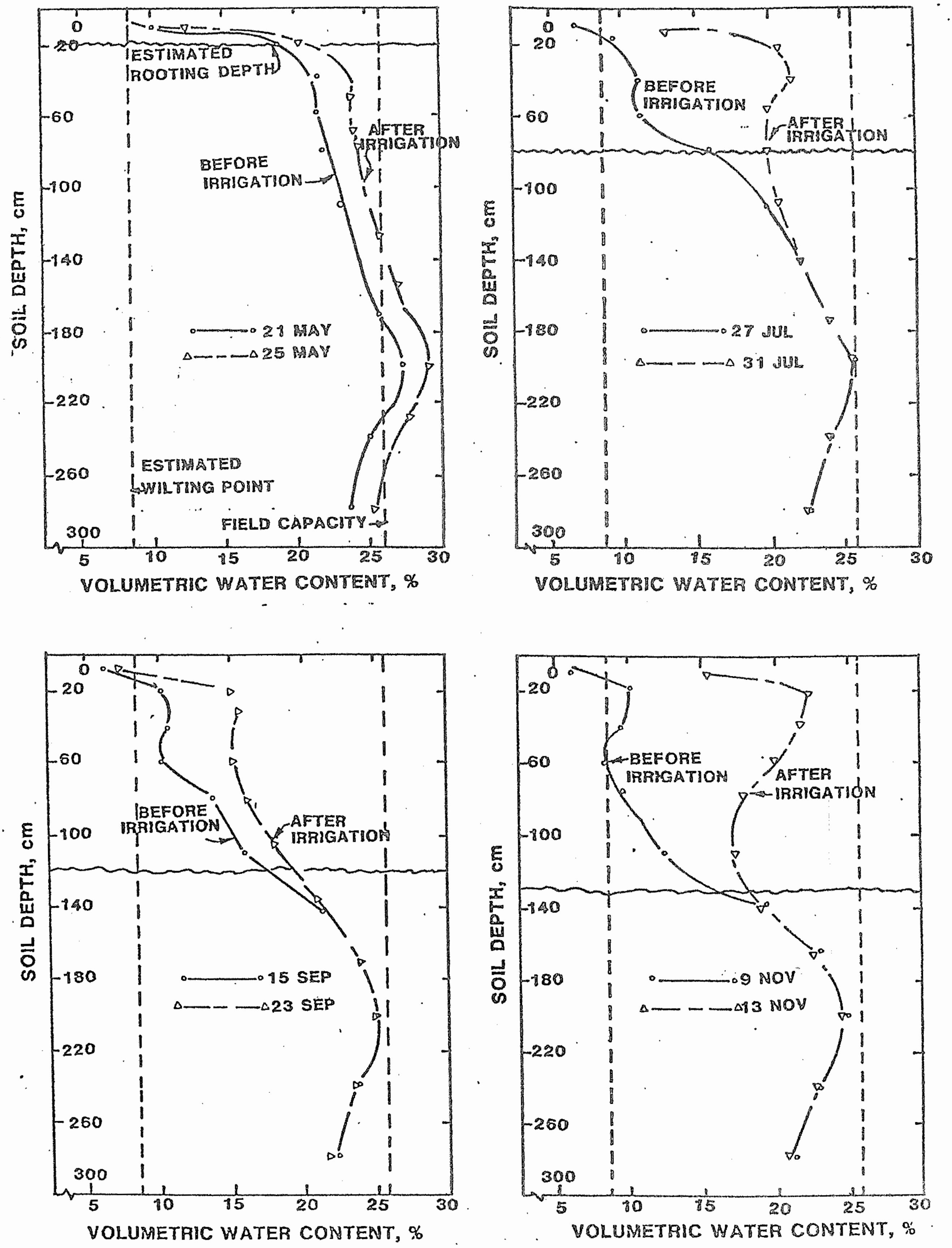


Figure 18. Soil water content profiles and estimated plant rooting depths for selected dates with the I_1 irrigation treatment at Mesa, Arizona, 1981.

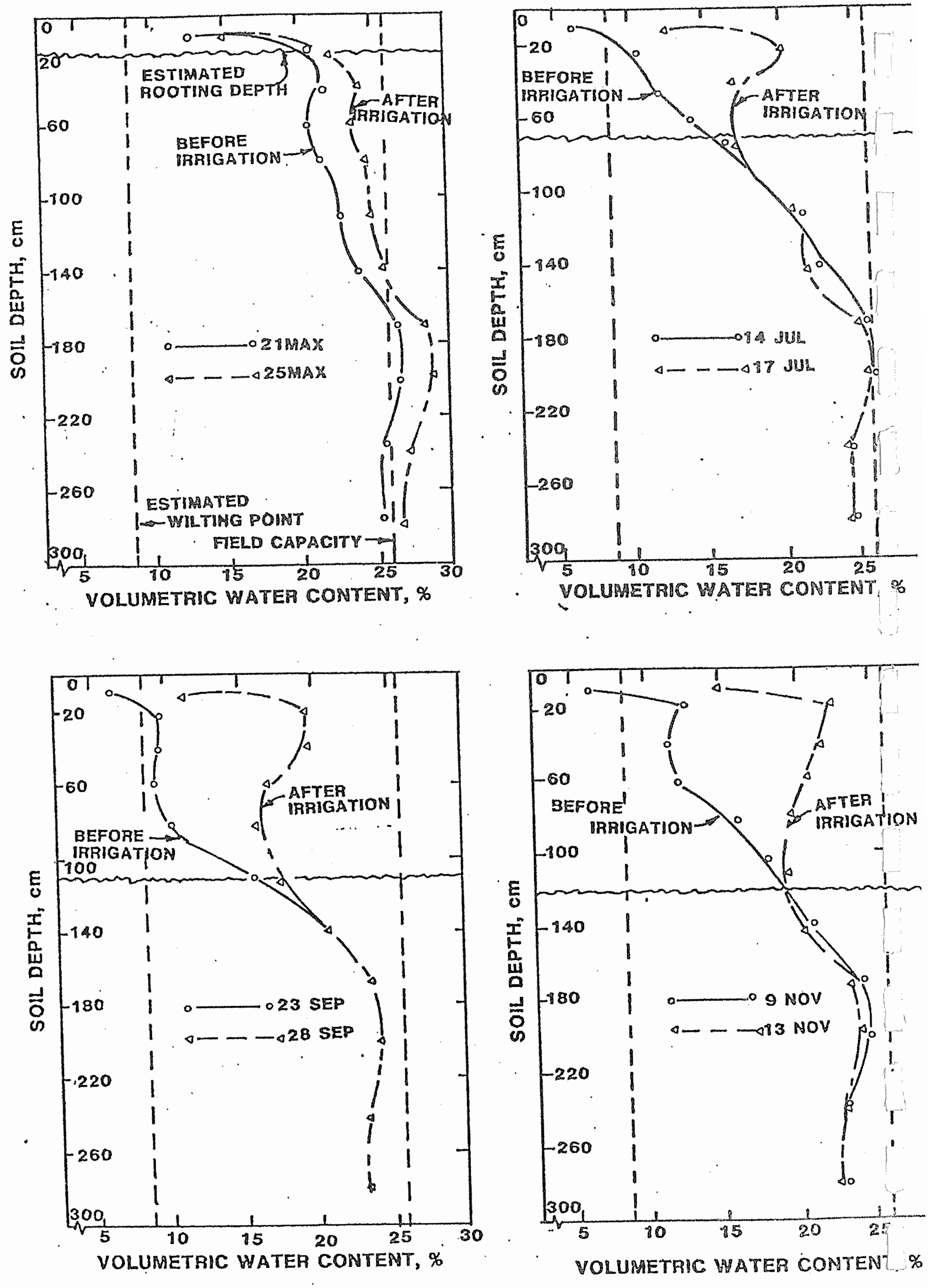


Figure 19. Soil water content profiles and estimated plant rooting depths for se dates with the I_2 irrigation treatment at Mesa, Arizona, 1981.

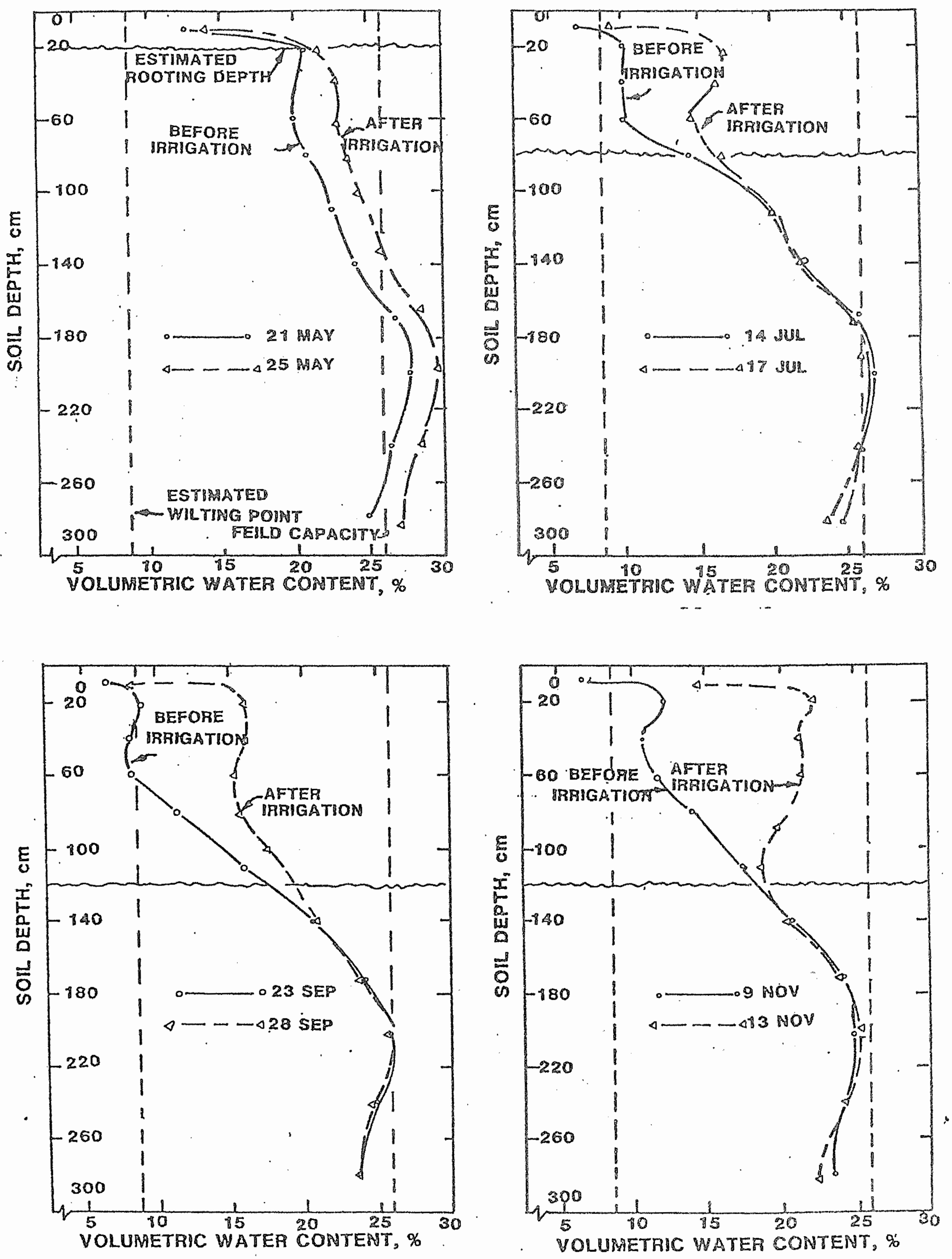


Figure 20. Soil water content profiles and estimated plant rooting depths for selected dates with the I_3 irrigation treatment at Mesa, Arizona, 1981.

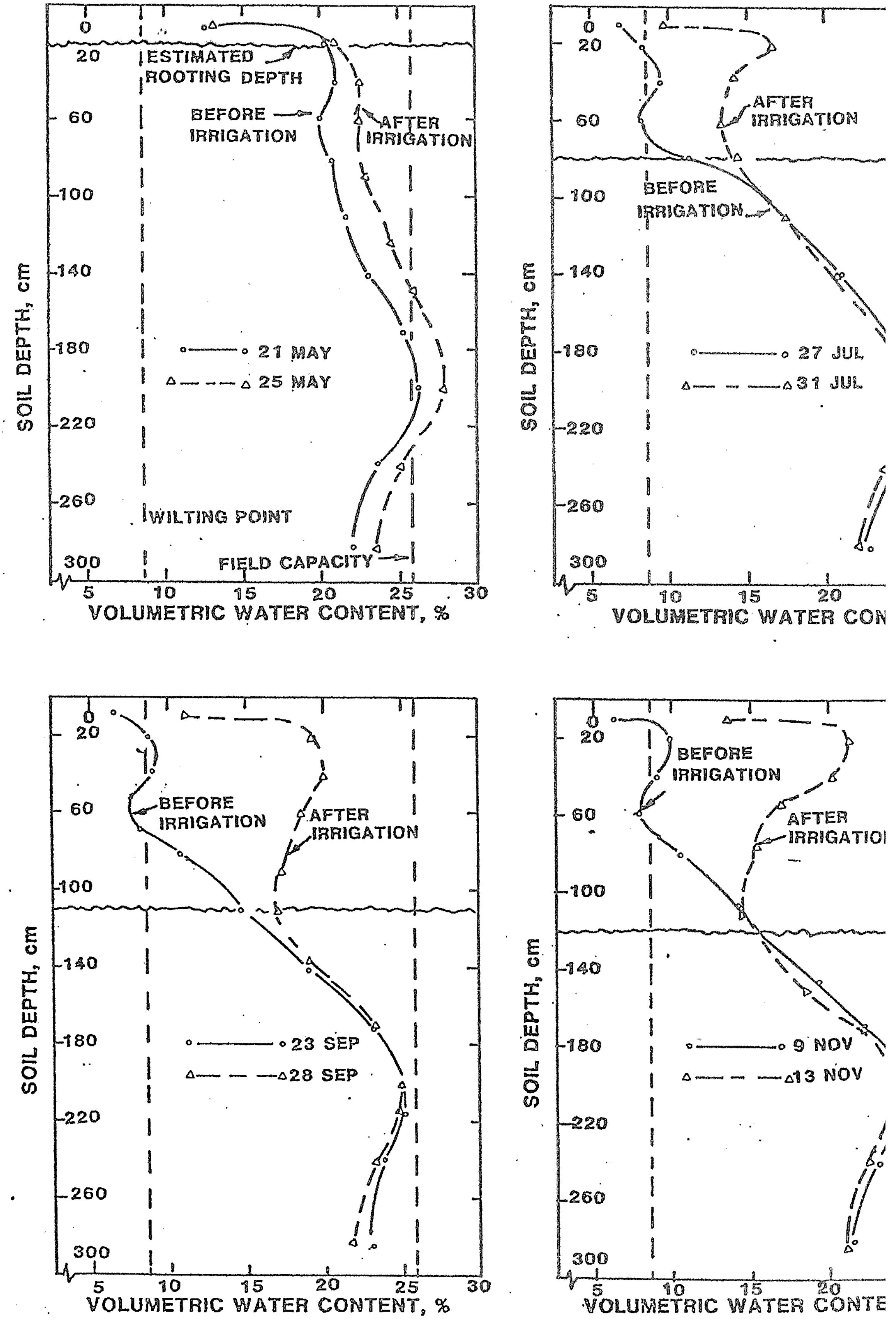
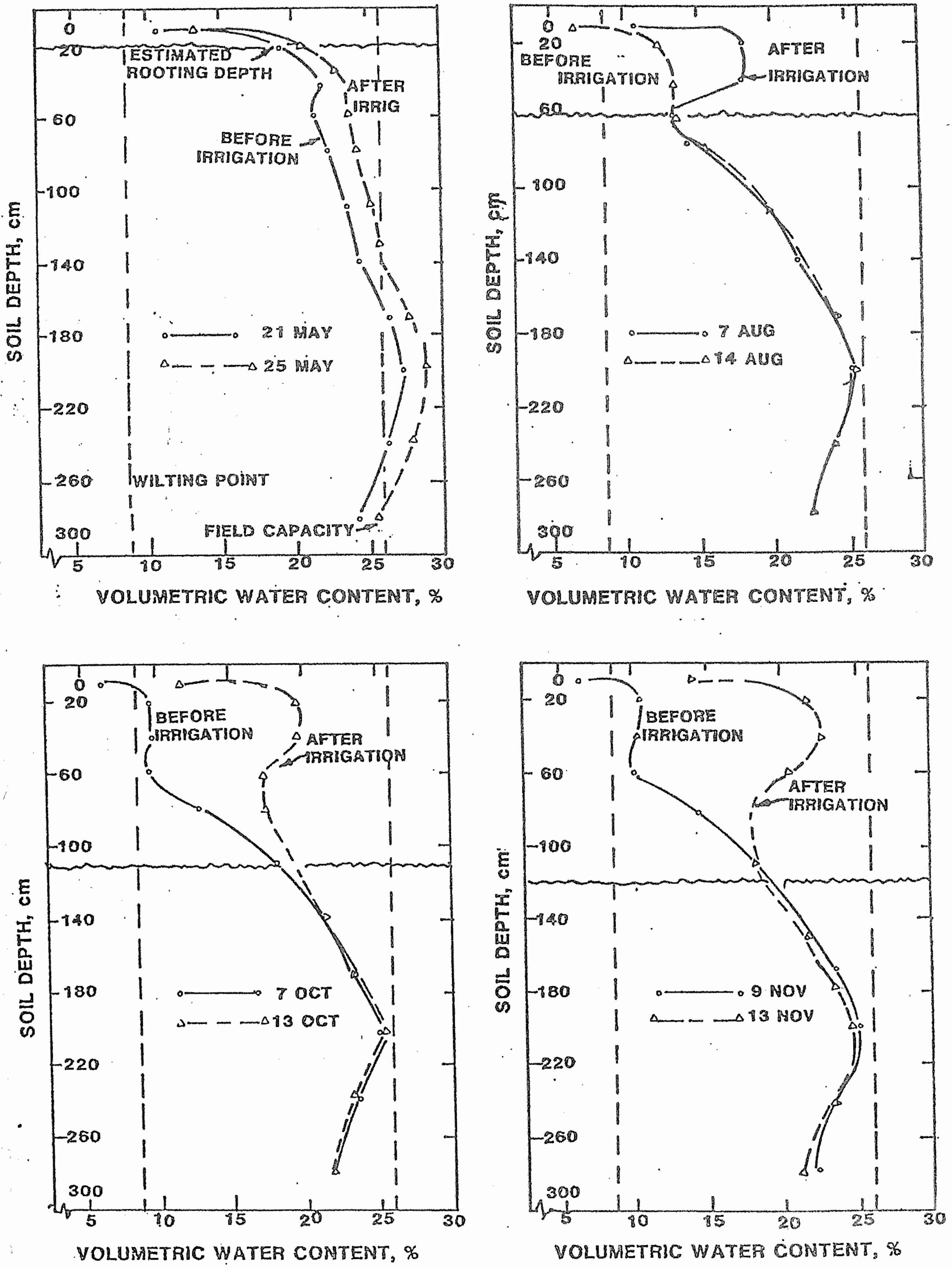


Figure 21. Soil water content profiles and estimated plant rooting depths f
dates with the I_4 irrigation treatment at Mesa, Arizona, 1981.



;ure 22. Soil water content profiles and estimated plant rooting depths for selected dates on the I_5 irrigation treatment at Mesa, Arizona, 1981.

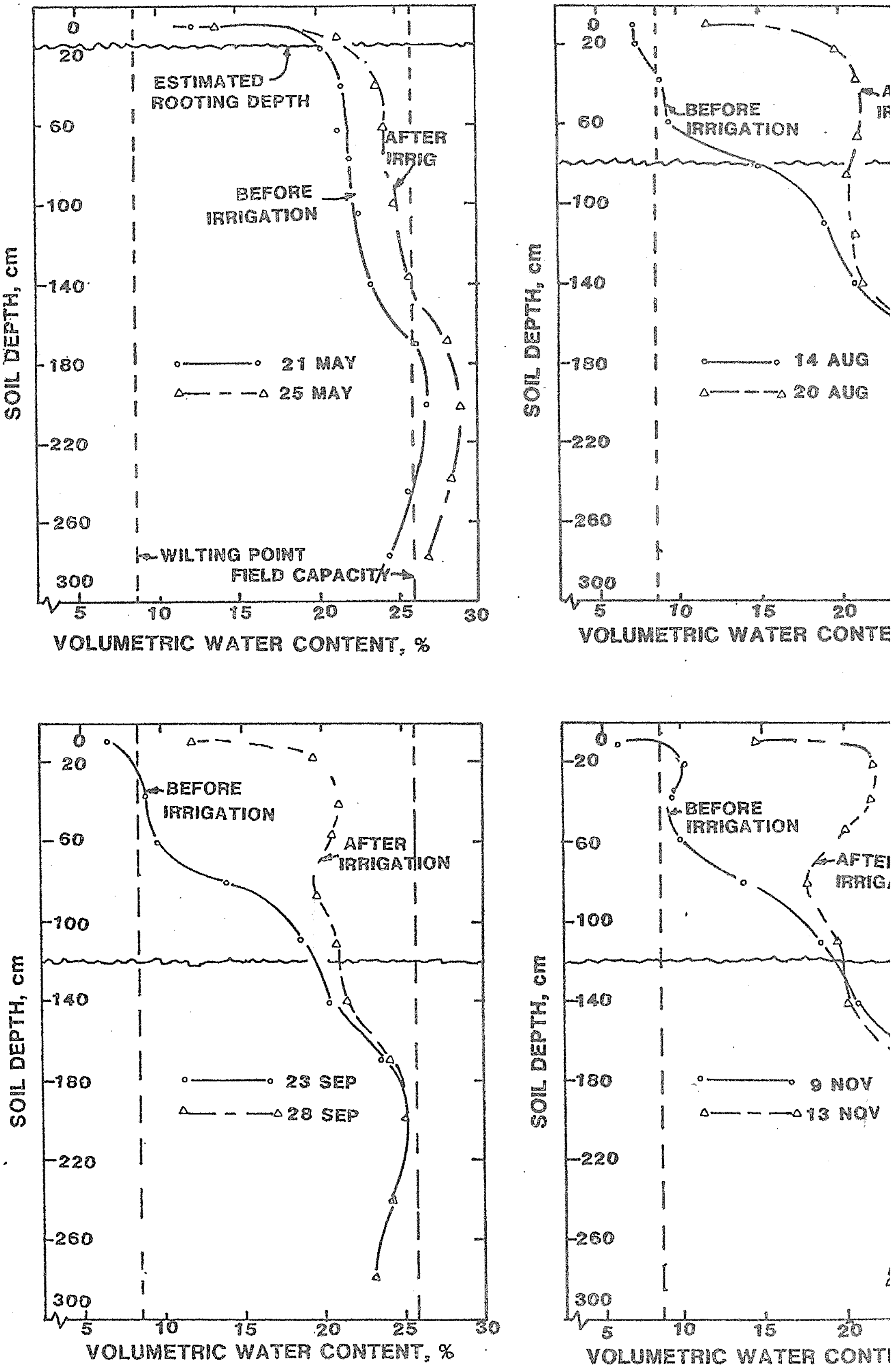


Figure 23. Soil water content profiles and estimated plant rooting depth
selected dates with the I[?] irrigation treatment at Mesa, Ariz

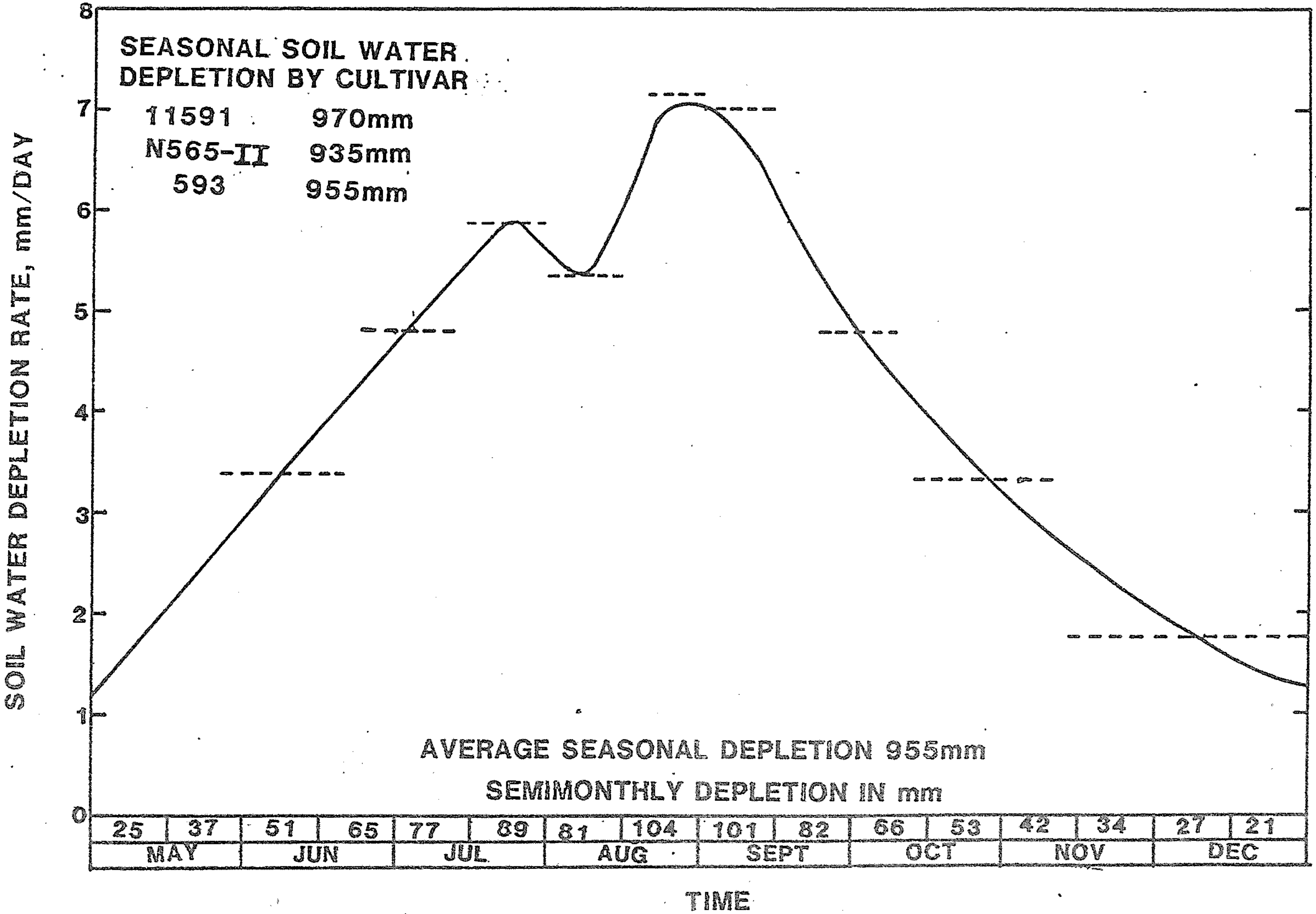


Figure 24. Measured soil water depletion for the I_1 irrigation treatment at Mesa, Arizona, 1981. (Seven irrigations were applied after July 1 when 74% of the available soil water was depleted in the 0-120 cm depth).

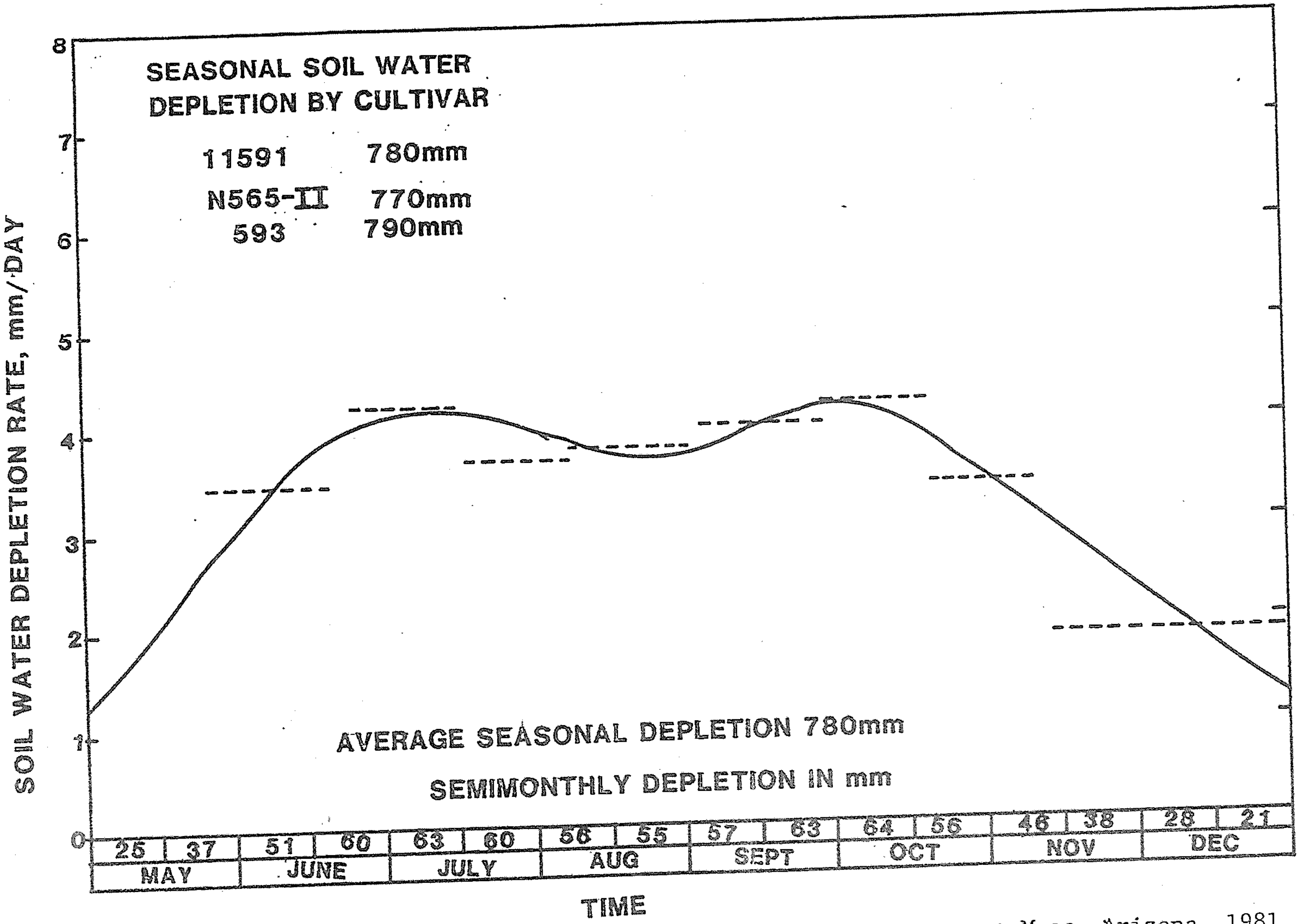


Figure 25. Measured soil water depletion for the I_2 irrigation treatment at Mesa, Arizona, 1981. (Six irrigations were applied after July 1 when 77% of the available soil water was depleted in the 0-120 cm depth).

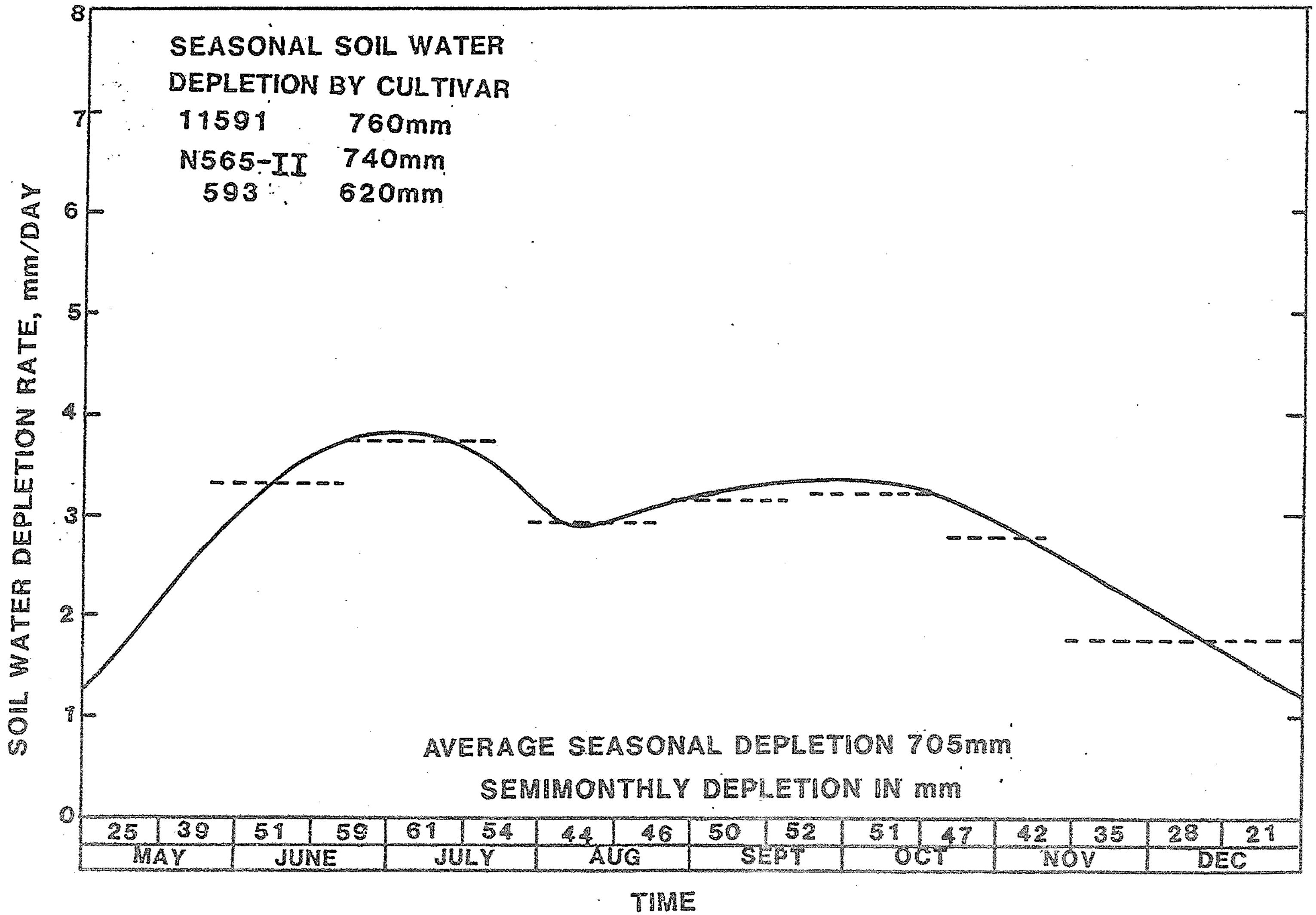


Figure 26. Measured soil water depletion for the I_3 irrigation treatments at Mesa, Arizona, 1981. (Five irrigations were applied after July 1 when 82% of the available soil water was depleted in the 0-120 cm depth).

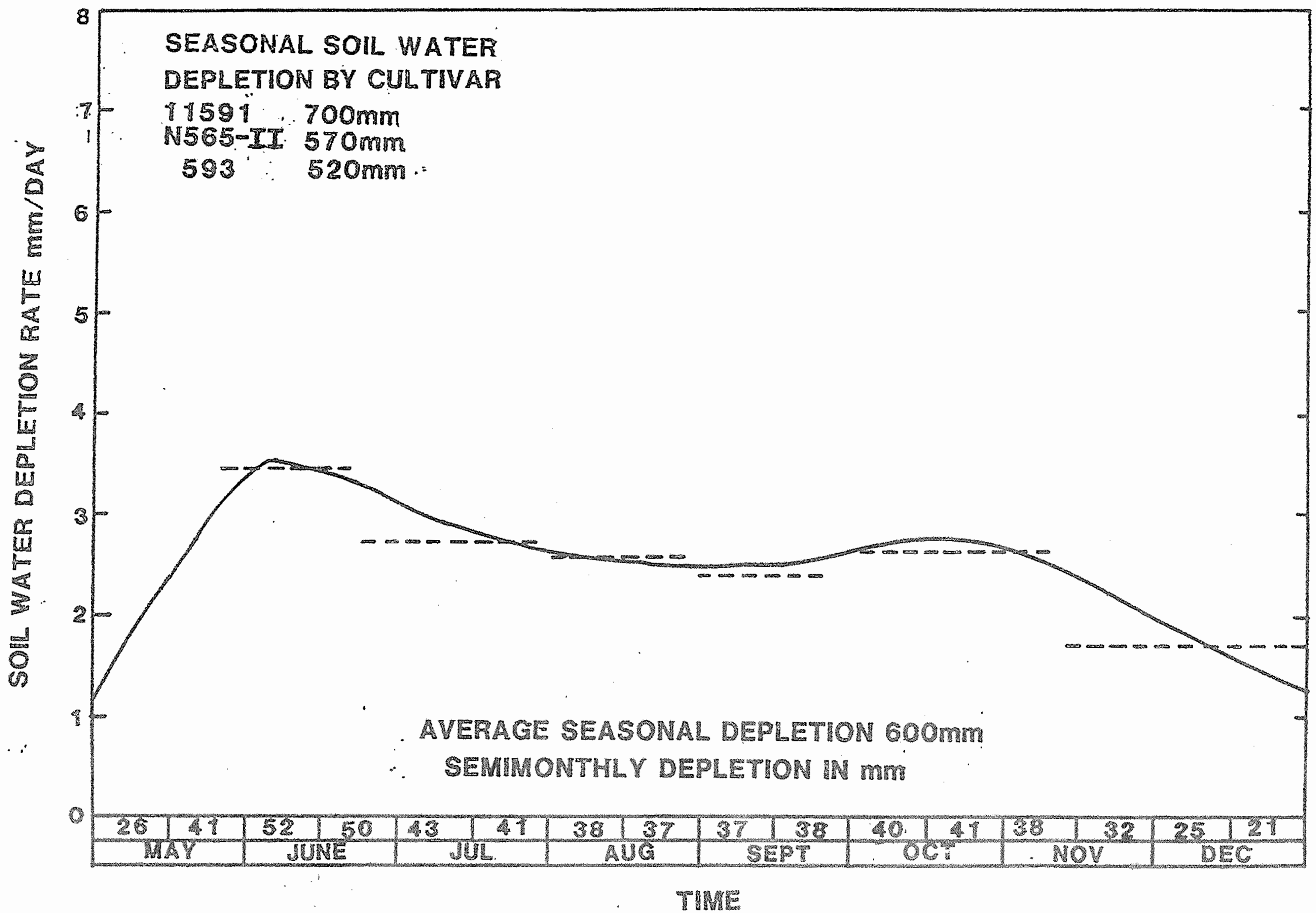


Figure 27. Measured soil water depletion for the I_4 irrigation treatment at Mesa, Arizona, 1981. (Four irrigations were applied after July 1 when 89% of the available soil water was depleted in 0-120 cm depth).

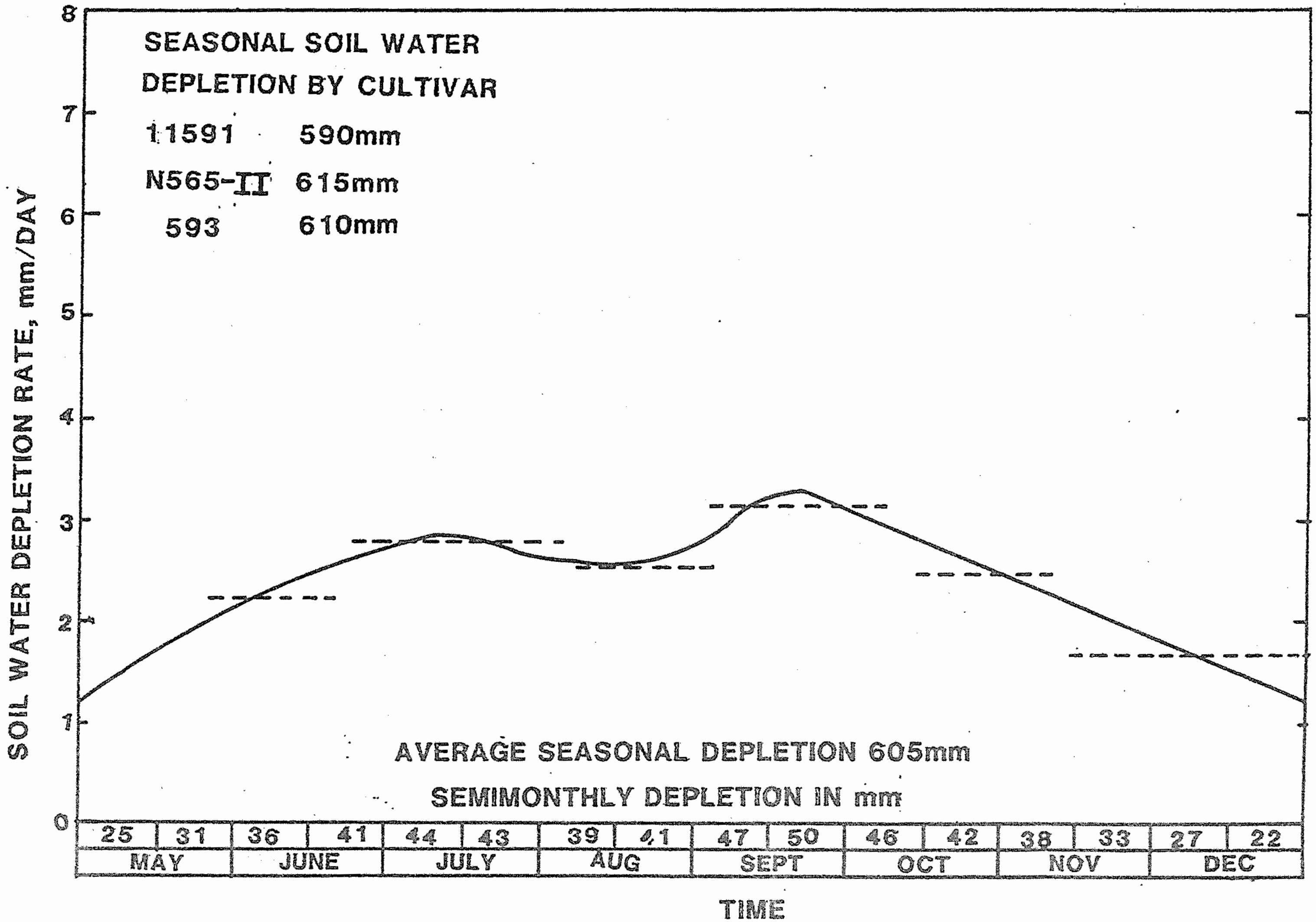


Figure 28. Measured soil water depletion for the I_5 irrigation treatment at Mesa, Arizona, 1981. (Four irrigations were applied after July 1 when 80% of the available soil water depleted in h te 0-120 cm depth).

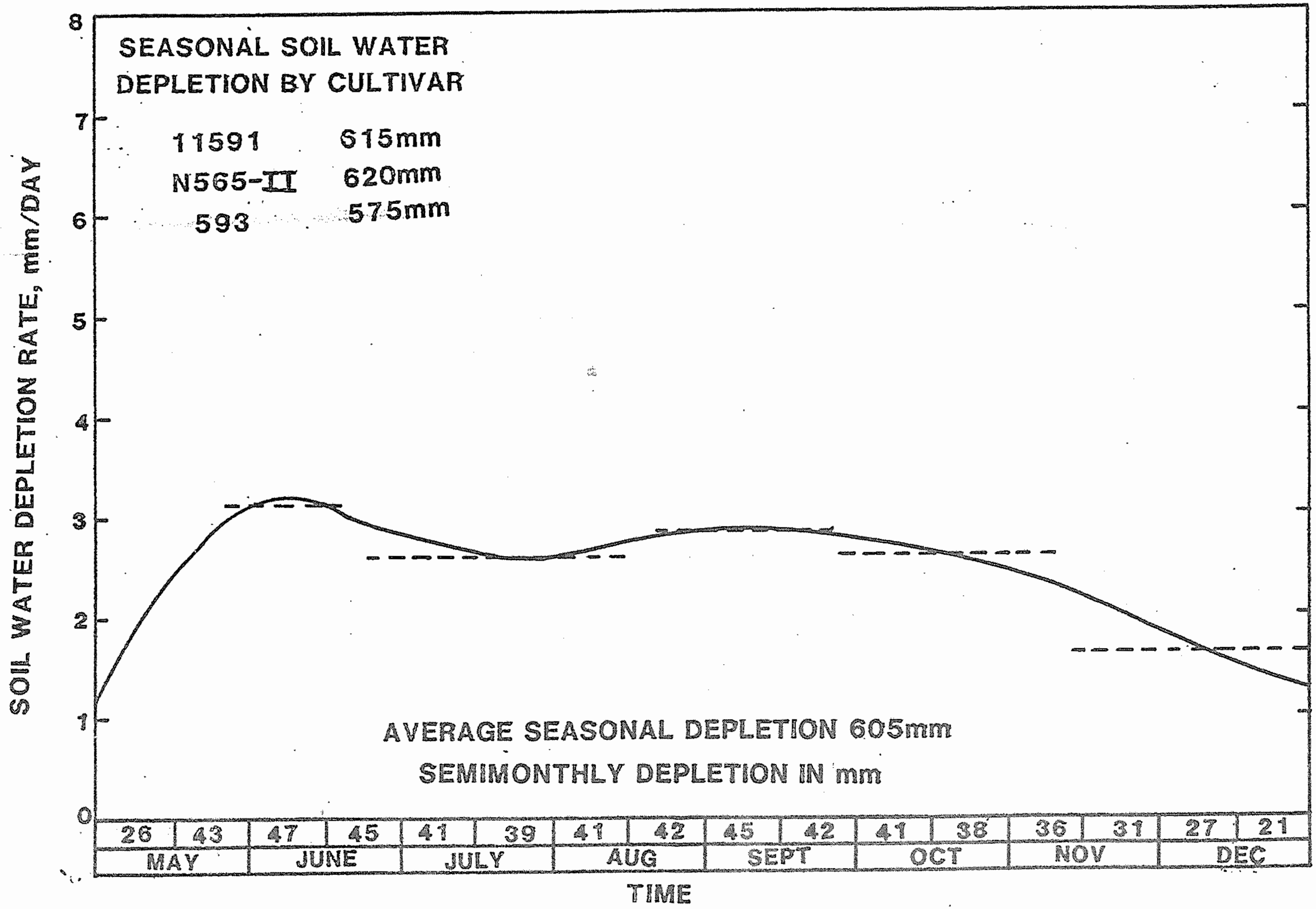


Figure 29. Measured soil water depletion for the I_6 irrigation treatment at Mesa, Arizona, 1981. Thr[illegible] irri[illegible]ons [illegible]e a[illegible]ied [illegible]er [illegible] 1 [illegible] 80% of the available soil water was depleted in the 0-120 cm depth).

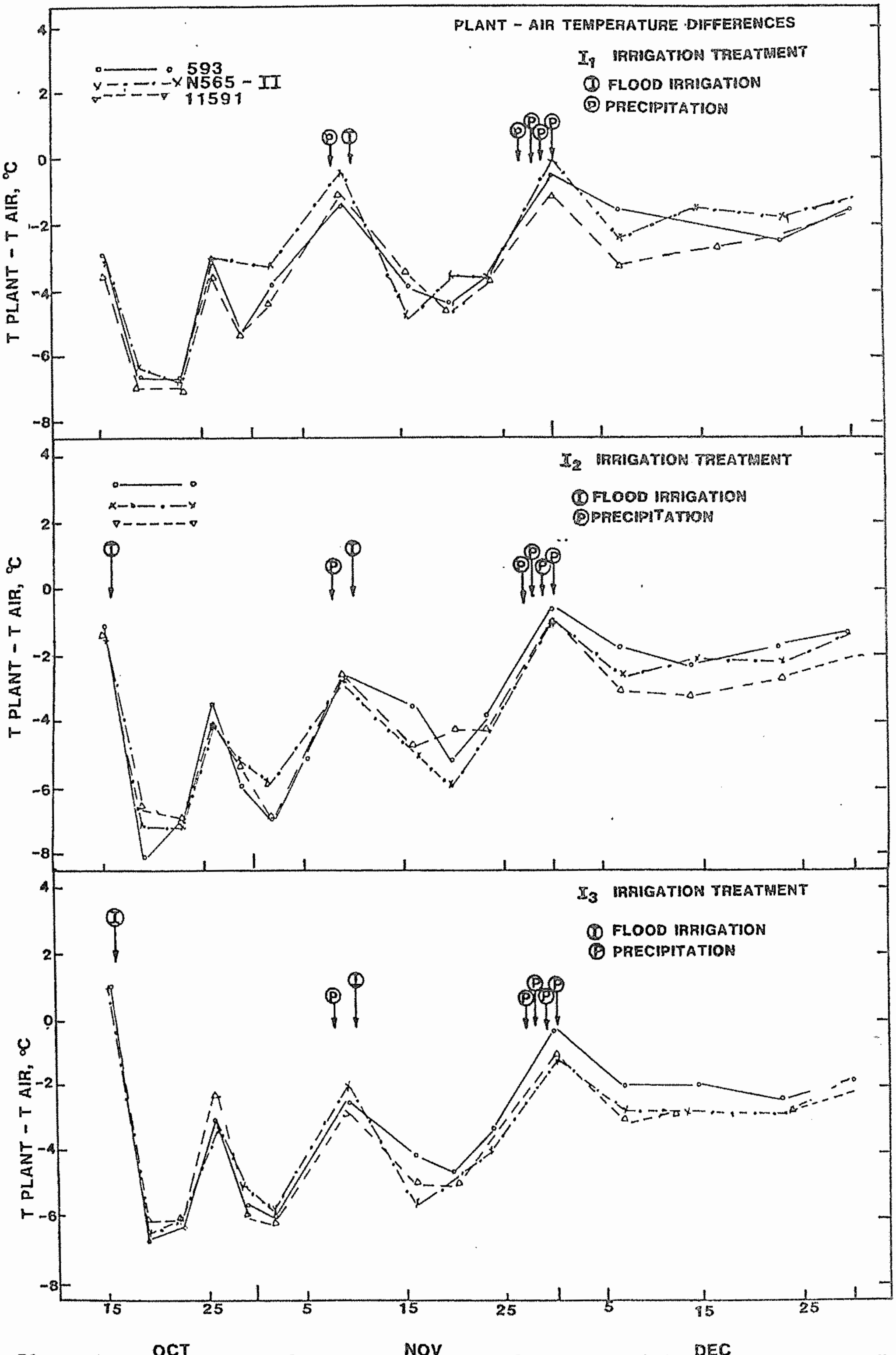


Figure 30. Plant-air temperature differences versus time for three cultivars under the I_1, I_2, I_3 irrigation treatments at Mesa, Arizona, 1981.

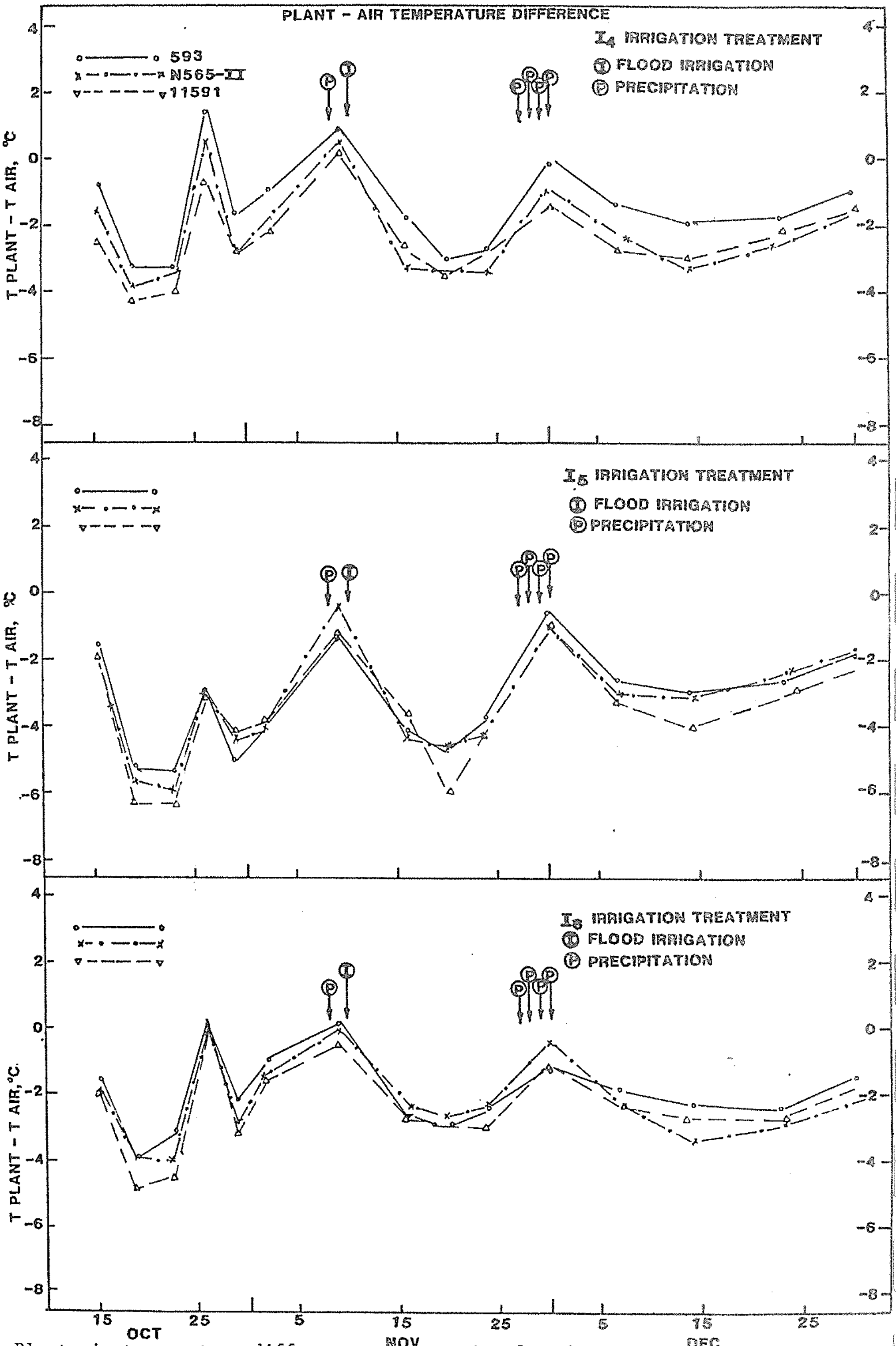
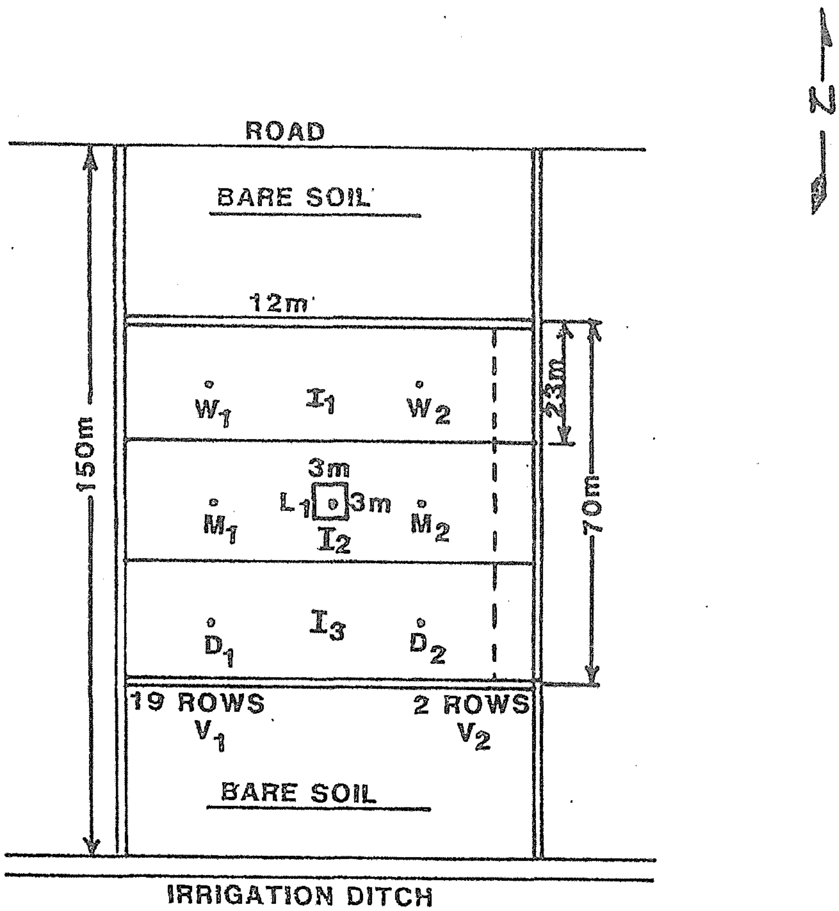


Figure 31. Plant-air temperature differences versus time for three cultivars under the I_4, I and I_6 irrigation treatments at Mesa, Arizona, 1981.

1981 BRAWLEY GUAYULE EXPERIMENT



LEGEND:

IRRIGATION TREATMENTS

I_1 = 60% SOIL MOISTURE DEPLETION IN A 0 - 120cm SOIL DEPTH
I_2 = 80% SOIL MOISTURE DEPLETION IN A 0 - 120cm SOIL DEPTH
I_3 = 100% SOIL MOISTURE DEPLETION IN A 0 - 120cm SOIL DEPTH

CULTIVARS

V_1 = 11591 V_2 = 593

ADDITIONAL INFORMATION:

LOCATION OF 7 NEUTRON ACCESS TUBES TO A 150cm SOIL DEPTH
PLANT SPACING: 51 x 36cm
PLANT POPULATION: 54,000 PER HECTARE
LYSIMETER DEPTH: 150cm

Figure 32. Plot diagram, irrigation treatments, and cultivars used at Brawley, California, 1981.

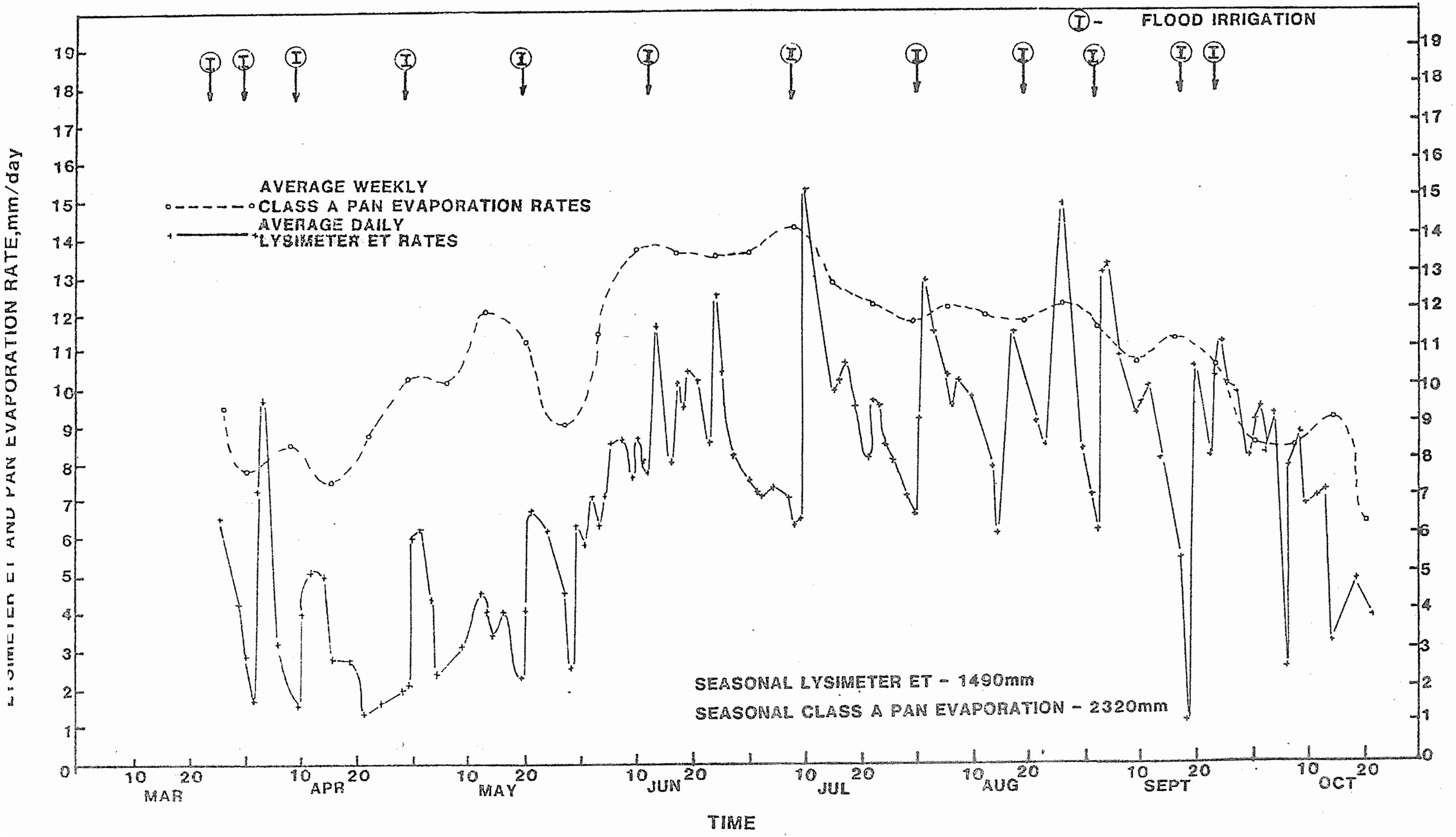


Figure 33. Measured daily lysimeter ET rates and average weekly class A pan evaporation rates at Brawley, CA, 1981.

TITLE: THE EVAPOTRANSPIRATION, YIELD, AND SOIL-PLANT-WATER RELATIONS OF GUAYULE

NRP: 20740 CRIS WORK UNIT: 5510-20740-012

INTRODUCTION:

The research in Mesa, AZ, was a continuation of the irrigation study reported on last year, i.e., four levels of irrigation with two cultivars, 593 and N565-II. The plants will be three years old on 29 May 1982. Plans are to harvest two times for rubber analyses and then to pollard (cut back) the plants in late spring to permit regrowth.

PROCEDURE:

(1) At Mesa, AZ. During the year, neutron meter measurements were made 56 times at 24 sites, at 8 depths per site. Irrigation was started in late March for the wettest treatment and in April for the others, and extended to October.

(2) At Phoenix, AZ. Intensive measurements of the relative leaf water content (RLWC) were made on cvs. 593 and 11591 under irrigation treatments designated as "wet", "medium" and "dry", accompanied by frequent measurements of soil moisture. These data were taken in conjunction with measurements of the difference between canopy and air temperature (described elsewhere) made with an infrared thermometer.

RESULTS:

(1) At Mesa, AZ. Table 1 and Fig. 1 summarize the data. In view of guayule's ability to extract soil water to increasingly lower values, all four irrigation treatments were made more stressful, resulting in a reduction in total number of irrigations in the wettest treatment from 25 to 16, for example, corresponding to a decrease in total irrigation water applied from 2289 to 2119 mm. The other treatments were reduced even more: No. 4, the driest treatment, going from 9 irrigations (a total water application of 1110 mm) to 4 irrigations totaling only 332 mm. Guayule in treatment No. 4 lowered the soil water content to the extremely low value of 0.045 by weight. This was considered the newly estimated wilting point.

(2) At Phoenix, AZ. Data on RLWC of guayule were presented in a paper given at the annual meeting of the Guayule Rubber Society, at the Caravan Inn, Phoenix, AZ., 13-15 October 1981. The abstract from that paper follows:

WATER STRESS IN GUAYULE AS MEASURED BY RELATIVE LEAF WATER CONTENT

The relative leaf water content (RLWC), defined as the ratio of the leaf water content just after collection to that at full turgor, was a sensitive indicator of soil water deficit in experiments at Phoenix, AZ.

RLWC ranged from near 100% in wet soil to near 30% when 95% of the available water in the upper 170 cm of soil was depleted. The RLWC of cv. 593 consistently was lower than that of 11591. Both cultivars responded overnight to an irrigation with a sharp rise in RLWC. Data are presented for several diurnal tests and season-long readings for RLWC taken at 1300 hours MST. The measurements will be continued until a full year of data is accumulated.

SUMMARY AND CONCLUSIONS:

The remarkable ability of guayule to extract water at extremely low soil water contents undoubtedly helps it to survive long droughts. For example, considering the 170-cm soil profile at the Mesa, AZ experimental site, lowering the estimated wilting point from that used initially, 0.08 by weight (valid for numerous common agronomic crops) to the current value of 0.045, increases the available water from 243 to 328 mm (using 0.18 by weight as the field capacity), a gain of 85 mm (3.3 inches).

PERSONNEL: W. L. Ehrler, D. A. Bucks, and F. S. Nakayama

Table 1. Treatment number, percentage of available soil water depletion in 170 cm of soil before irrigation, number of irrigations, and the total amount of water applied [in addition to 146 mm (5.8 inches) of rain] to guayule cultivars 593 and N565-II.

Trt. No.	% Depletion	No. of Irrigations	Total Water Applied	
			mm	Inches
1	80	16	2119	83.4
2	84	9	957	37.7
3	89	6	491	19.3
4	92	4	332	13.0

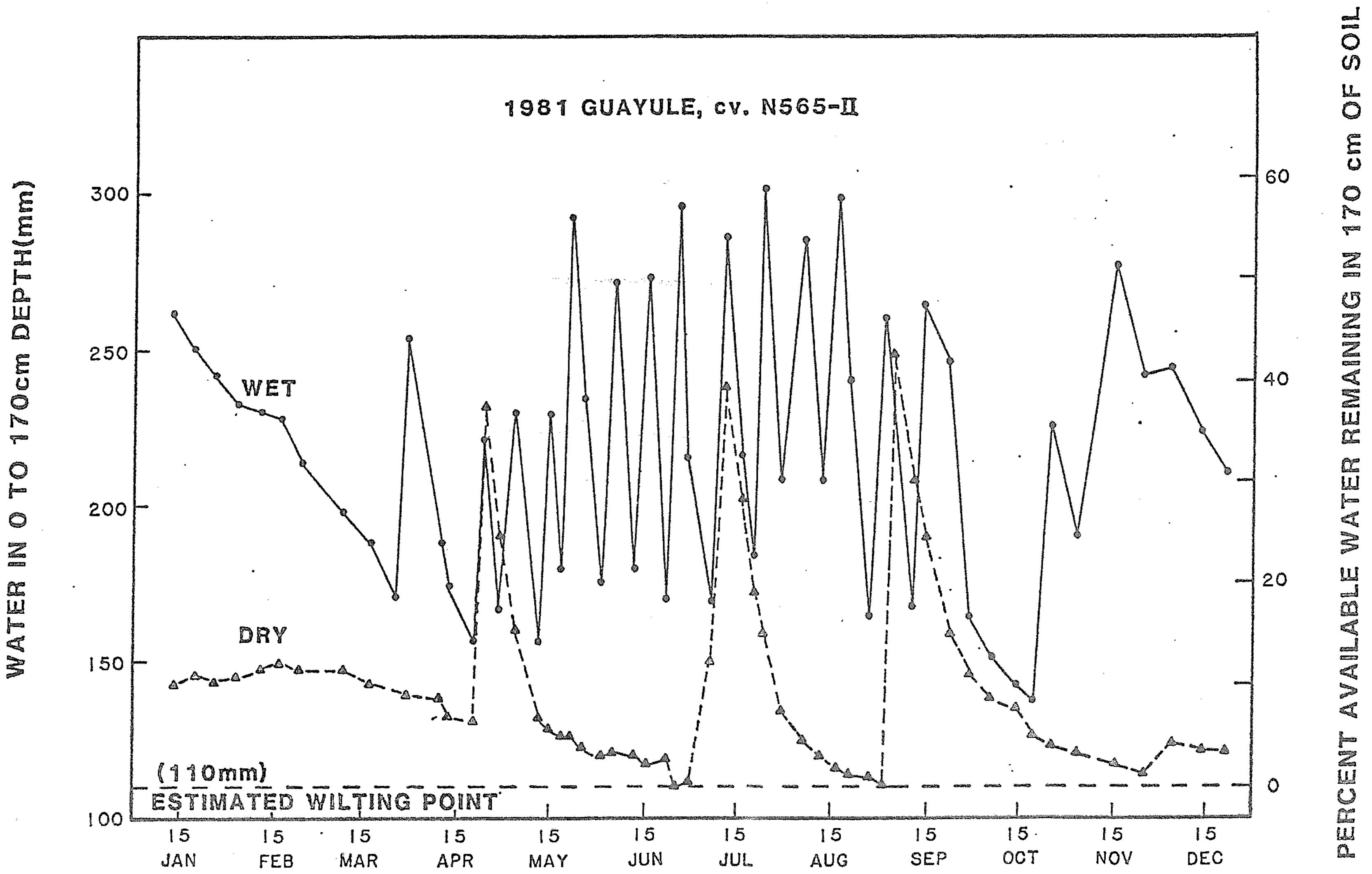


Figure 1. Changes in water content of the soil profile (0 to 170 cm) and the corresponding decreases in water availability in the wettest and driest of four irrigation treatments of guayule (cv. N565-II) at Me[illegible] AZ [illegible]1981

TITLE: VOLATILE COMPONENTS OF THE GUAYULE PLANT

NRP: 20740 CRIS WORK UNIT: 5510-20740-012

INTRODUCTION:

World-wide predicted shortfall and economic uncertainties of rubber availability from the hevea plant (Hevea brasiliensis) have renewed interest in using alternative natural sources such as the guayule (Parthenium argentatum), a native of arid Northern Mexico and the Southwestern United States. Extensive research has begun recently on the agricultural production and industrial processing of guayule rubber and resin by-products. Estimates indicate that several million hectares are needed to make the guayule rubber industry a viable entity.

The guayule plant is able to synthesize cis-1,4-polyisoprene, which has similar properties as the hevea rubber polymer (NAS, 1977). Other isoprene-related polymers, including a contact allergenic sesquiterpene, have been identified in the plant parts. (Bonner, et al. 1950; Rodriquez, et al. 1981). The reason for the plant to make isoprene and its polymers is not well understood, although theories have been proposed on the mechanism of isoprene synthesis, probably as a result of photorespiration.

Studies have shown that isoprene and other hydrocarbons are emitted from a variety of plants (Rasmussen, 1970; Zimmerman, 1979), but that air quality doesn't seem to be significantly affected by such vegetative emissions (Bufalini, 1980). Furthermore, a possible anticarcinogenic role has been attributed to isoprene (Blondell, 1981). Since isoprene products are synthesized by guayule, similar types of hydrocarbon emissions could occur with this plant. Investigations were started to identify the volatile compounds emitted by guayule.

PROCEDURE:

The atmosphere immediately surrounding the 18-month old guayule plant, Variety 11591, was sampled in the morning of 24 July 1981 using a portable sampling device (Zimmerman, 1979b), supplied by Dr. Zimmerman of the National Center for Atmospheric Research, Boulder, Colorado. A transparent plastic bag was spread over the individual plant approximately 60 cm high and 50 cm in diameter and the air circulated within the enclosure for 10 minutes, after which gas samples were collected in 2-liter stainless steel evacuated containers. Temperatures of the plant, the inner and ambient air, and radiation were monitored during the sampling period. Infrared plant temperature measurement of adjacent plants showed leaf temperature below the ambient air and indicating that the stomates were open and the plants were not under a moisture stress. The set of plants used was from a well-watered plot which was part of an irrigation experiment at Phoenix, Arizona.

Background and plant emitted gases were analyzed for the various constituents with the gas chromatography/mass spectrometer technique (Zimmerman 1979b), in cooperation with Dr. Zimmerman.

RESULTS AND DISCUSSIONS:

Hydrocarbon analyses of the gases collected from two guayule plants are presented in Table 1. Isoprene and ten other isoprene-related compounds were identified in the volatile sample. From data available on similar types of analysis, the isoprene to α-pinene and β-pinene relations are different between the guayule and other plants. For Turkey oak (*Quercus laevis*) isoprene 23.43, α-pinene = 0.37, and β-pinene = 0.15 mg/g/hr; and Live oak (*Quercus virginiana*) isoprene = 9.08, α-pinene = 0.05, and β-pinene = 0.06 mg/g/hr (Zimmerman, 1979a). Other data available, where isoprene has been identified indicate that isoprene emission is as high if not higher than the other hydrocarbon components emitted, so guayule behavior in this regard is different from these other species. Nine of the hydrocarbon compounds of Table 1 except isoprene and α-thycene were identified recently in redwood (*Sequoia semperuivens*) by Okamoto et al, 1981.

Based on historical yields of 500 to 800 kg rubber per hectare, the emission loss of isoprene-hydrocarbons could play a significant role in total of the hydrocarbon synthesis and balance of the guayule plant. Further investigations are being conducted to relate hydrocarbon emissions for the guayule plant in respect to plant age and variety, moisture stress, fertility level, time of day, climatic conditions, and resin and rubber production.

SUMMARY:

Eleven hydrocarbon compounds including isoprene, the basic rubber unit, and isoprene-related hydrocarbons were identified in the volatile fraction of the guayule plant. The isoprene fraction is lower relative to the other hydrocarbons unlike other plant species. Preliminary measurements and emission rate from guayule indicate that the volatile hydrocarbons could be a significant part of the total hydrocarbon synthesis and balance of the plant.

REFERENCES:

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Blondell, J. M. 1981. Isoprene: A possible anticarcinogen. Medical Hypothesis. 7:333-334.

Bonner, J. 1950. Plant Biochemistry. Academic Press Inc., New York. 537 pp.

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Okamoto, R. D., Ellison, B. O., and Kepner, R. E. 1981. Volatile terpenes in Sequoia sempervirens foliage. J. Agric. & Food Chem. 29:324-326.

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Rodriquez, E., Reynolds, G. W., and Thompson, J. A. 1981. Potent contact allergen in the rubber plant guayule (Parthenium argentatum). Science 211:1444-1445.

Zimmerman, P. R. 1979a. Determination of emission rates of hydrocarbons from indigenous species of vegetation in the Tampa/St. Petersburg, Florida area. EPA Rept. 9049-77-028. U. S. Environmental Protection Agency, Atlanta, Georgia.

Zimmerman, P. R. 1979b. Testing of hydrocarbon emission from vegetation, leaf litter and aquatic surfaces, and development of a methodology for compiling biogenic emission inventories. EPA Rept. 450/4-79-004. U. S. Environmental Protection Agency, Research Triangle Park, North Carolina.

PERSONNEL: F. S. Nakayama

Table 1. Components and emission rates of guayule volatiles (μg/g leaf biomass/hr).

Compound	Plant A	Plant B
	μg/g/hr	μg/g/hr
Isoprene	0.340	0.210
Unidentified	0.009	0.008
α-thycene	0.021	0.005
α-pinene	3.621	2.745
Camphene	0.222	0.192
β-pinene	1.834	1.459
Myrcene	0.096	0.063
α-phelladrene	0.028	0.031
β-phelladrene	0.012	0.007
Sabinene	0.050	0.036
Limonene	0.493	0.434
Ocimene	0.070	0.101
Total Emission Rate of Major Components	6.456	5.081
Total Emission Rate*	6.4	5.0

*This emission rate is slightly smaller than the emission rate of the major components alone. This is due to the difficulty in quantifying oxygenated compounds and absorption of some compounds in condensed water and/or on leaf surfaces during the enclosure period.

TITLE: RUNOFF-FARMING FOR DROUGHT-TOLERANT CROPS IN ARID ENVIRONMENTS

NRP: 20760 CRIS Work Unit: 5510-20760-002

INTRODUCTION:

We have several runoff farming studies in progress. The following lists them chronologically by year of installation and by crop, and briefly summarizes the experimental objectives, approaches, and major findings to date.

JOJOBA: (Initiated in 1973). The primary objective was to determine if the seed yield of native jojoba plants could be increased substantially by supplementing the limited precipitation with runoff water from small adjacent catchments. A secondary objective was to try to quantify the plant's water requirement when grown using runoff farming.

We selected 30 marginal bushes from near the dry limit of a native stand. There were three water levels of 10 bushes each: control bushes which received only precipitation, and two higher water levels in which the precipitation was supplemented with runoff from two types of treated catchments (Ehrler and Fink, 1978).

The major finding of the study was that jojoba needs considerably more water to produce a substantial crop then previously supposed. The average amount of water supplied to the plants in our study during the seven year period from October 1973 through September 1980 was 1.0, 3.3, and 5.7 feet respectively for the three treatments. The extra water supplied by the highest level runoff treatment spurred both plant growth and seed yield: 50 and 350 percent increases respectively over controls by the fifth year.

Little or no increase in growth over controls occurred for plants receiving the intermediate water level; this suggests that a threshold water requirement exists separating mere survival from significant growth and yield.

Clearly, the oft touted five-inch water requirement for jojoba probably is insufficient even for plant survival. Under such arid conditions the plant can only survive in washes which occasionally receive natural runoff water.

This discovery that jojoba, like common mesophytes, requires ample quantities of water to produce an ample crop, may extend to other desert plants currently being considered for cropping in arid and semiarid climatic regions.

Other findings from our jojoba study were less encouraging for the use of runoff farming for this crop. The extra water harvested from the summer/fall rains would usually trigger a late season vegetative flush, and seemed to hasten onset of spring flowering. Both physiological responses increased the plant's vulnerability to frost damage. Spring frosts destroyed the flowers and developing fruits of the runoff-farmed plants three years out of the first six. An especially sharp freeze in 1979 destroyed most of the unhardened growth from the previous fall's flush. Several of the runoff-farmed plants actually were killed back to the crown. Contrarywise, control bushes experienced little damage.

There are claims that the plant has no serious insect pests. Our results refute this claim. Grasshoppers severely damaged the plants several years. The worst pest, however, has been an unidentified larva which feeds on, burrows into, and destroys the newly developing fruits. We have experienced significant losses several years. The insect seems to prefer the vigorous fruiting bodies of the runoff-farmed plants, but even of these, some bushes are more vulnerable to attack than others. In 1981, there was essentially no flowering nor fruit set on the bushes throughout the Usery Pass area because of a drought the previous year. The few runoff-farmed plants, however, flowered as usual. The local emerging adults of the boring larvae descended on the handfull of flowering jojoba plants to lay their eggs. The crop was decimated. Several entomologists are attempting to identify the insect.

In spite of these setbacks, runoff farming for jojoba still has much potential. It should work well in Mediterranean climates, as in southern California and northwestern Mexico, where most of the precipitation occurs in winter, and the summer/fall season is extremely dry. This rainfall pattern should prevent late season second flushes of growth, should allow the plants to harden against both drought and frost, and should help delay flowering beyond most spring freezes.

Runoff farming should still be practical for jojoba in Arizona and other similar locations which receive both winter and summer precipitation, provided either that the summer runoff is diverted away from the plants or is quickly exhausted from soil storage by intercropping the jojoba with a short-season fall annual.

The figures listed earlier regarding the amount of water supplied to the runoff-farmed jojoba bushes in this study cannot be extrapolated directly to conventionally irrigated plantations. One reason is that the runoff water from the catchments was concentrated within a small $4m^2$ growing area, not over an area comparable to regularly spaced plantation plants. A second reason is that conventional irrigations probably would be concentrated during late winter/spring to coincide with flowering and seed development, then drastically reduced during the summer/fall period. Thus the contribution from the summer/fall rains in our studies probably must be subtracted from the actual water needs of the crop. A third reason is that many of the small rains probably do not benefit the plants. The water is largely lost by direct surface evaporation. Such small rains can constitute a significant portion of a year's precipitation. Still a fourth reason is that excessive amounts of runoff from large storms may seep beyond the plant's root zone and be lost.

Clearly, more research is needed on the use of runoff farming for growing jojoba. This drought tolerant desert plant still holds much promise for cropping new and abandoned farm land where irrigation water is unavailable, too expensive, or of inferior quality; where the only or primary source of water is that suppliable by runoff farming.

Christmas Trees at Granite Reef: (Initiated in 1978).

The objective was to determine if a high value crop, Christmas trees, could be grown successfully in an arid climate using only runoff farming to supply the needed supplemental water.

Individual $20m^2$ water-harvesting catchments for supplying three levels of water to individual $4m^2$ growing areas were built, and the $4m^2$ growing areas were planted with Quetta pine seedlings. This tree is acclaimed to be drought tolerant and fast growing, and to make beautiful Christmas trees.

Results from this study have been discouraging. After almost four years only 11 live trees of the original 25 remain; and those which remain are barely surviving. The tallest trees are still less than three feet tall which is far short of the three-feet or more of anticipated growth per year. We can only speculate on reasons. There should have been adequate water, especially for those trees receiving the highest water level (estimated to average 5.5 ft/yr, but ranged from 9.1 to 3.0 ft/yr during the four years).

The soil, however, has a low water holding capacity. Undoubtedly, much of the runoff water (especially from larger storms) was lost below the tree's root zone. Root development has been slow, possibly because of a lack of a microbial population on this recently introduced exotic, or possibly because of high soil temperatures.

Mulching or inoculation with mycorrhizae may be beneficial. Certainly, better adapted species exist which would grow and prosper at this harsh site using the water supplied by runoff farming.

Horticultural Crops at Usery Pass: (Initiated in 1978).

The objective of the study was to screen a number of horticultural crops for runoff farming for future in-depth studies. Individual $20m^2$ catchments were built to supply water to $4m^2$ growing areas for each plant. The soil at Usery Pass is even droughtier than that at Granite Reef, yet a number of plants were established and have managed to survive and grow: almonds, grapes, a pomegranate, a jujube, a fig and a pistachio. Those which did not survive were an apricot, a peach, an olive, one species of grape, and one of the two pistachios. A fig apparently was killed by frost the first winter. The grapes have yielded two small crops and several of the other species should be yielding soon.

Christmas Trees at Camp Verde: (Initiated 1979).

As at Granite Reef, the objective was to use runoff farming to produce a valuable crop - Christmas trees. We anticipated better success at Camp Verde than at Granite Reef because the rainfall is greater (12 vs 8 inches annually, respectively) and because temperatures at Camp Verde are milder.

We established two runoff treatments (one each on two sites), three water levels at each site, and two tree species at each site/water level combination. The runoff treatments were NaCl salt on a clay soil and wax on sand; the projected water levels were 2, 3, and 4 times the 12-inch average precipitation; the trees were Arizona cypress and Quetta pine.

We harvested 120 of the original 300 trees in December 1981. They had attained marketable size in only three growing seasons. The Arizona cypress on the sand site were clear-cut (75 trees) since practically all were of marketable size. The other 45 harvested trees were from scattered locations within the remaining three tree/site combinations. Table 1 lists the number of marketable trees by soil site, water level and species.

If the remaining trees continue their rapid growth, most will be harvestable in 1982. However, much research is still needed. The runoff treatments must be improved. The wax treatment must be made durable enough to last ten rather than the currently anticipated four or five years. Otherwise the harvested water will be too expensive. Clay which washes off the salt treatment seals the surface of the runon cropped area. Water infiltration on the cropped area must be increased and clay transport off the catchment area must be decreased. The Quetta pines have done poorly on the sand site (high mortality and low growth rate), just as at Granite Reef. Reasons and solutions are needed - especially because this pine has ready consumer acceptance as a Christmas tree. Information also is needed on other standard cultural practices when the trees are grown using runoff farming: pest control, fertilization, shearing and stump culturing.

Conifers at 3-Bar: (Initiated in 1980).

The objective of this runoff-farming study was to establish conifers on a site that had previously been converted from chaparral to grass. Conifers should have greater economic potential than chaparral, and would provide an esthetically pleasing mosaic. Such scattered growth of trees would also be of benefit to wildlife.

The replicated experiment had two water levels: controls getting only precipitation (estimated to be 20 inches per year), and another receiving runoff from a repellent-treated runoff catchment. The conifers were Arizona cypress and Quetta pine. Results to date are encouraging but inconclusive.

Christmas Trees at Camp Verde: (Initiated in 1981).

The objective of this runoff-farming study was to evaluate a drip irrigation system for establishing the trees. As with the other experiment at Camp Verde, there are two tree species (Quetta pine and Arizona cypress) and three water levels (2, 3, and 4 times the normal 12 inches of precipitation). There will be only one runoff treatment (wax) which will be applied in 1982.

The study will be extended in 1982 to use the drip system to supplement the runoff water during the spring/summer rainless period which usually extends from March to July. Tree growth parameters will be compared to those obtained in the earlier study in which the trees received only runoff water plus the precipitation.

CONCLUSIONS:

We have six runoff farming experiments in various stages of progress: one with jojoba, one with horticultural crops, and four with conifers (three for production of Christmas trees and one for upgrading chaparral). In five of these, the supplemental water is supplied only by concentrating and directing the local precipitation from adjacent runoff catchment areas to the growing area. In one experiment, a drip irrigation system was installed to aid in the establishment of the Christmas trees, and to provide a small amount of irrigation water during the critical spring/summer period when rainfall is minimal and growth conditions are optimal.

The major finding to-date have been: (1) jojoba requires considerably more water to grow and produce than published estimates have claimed. Probably most xerophytic desert plants currently being considered for cropping require considerable amounts of water to produce a substantial crop. If this is so, they will be poor candidates for conventional irrigated agriculture; if they don't save water these plants will have no advantage over proven, high-producing, convential mesophytic plants. However, the ability of desert plants to withstand severe and prolonged drought does make them prime candidates for runoff farming. Furthermore, information on the water needs of these new crops obtained using conventional irrigation probably will not apply to runoff farming situations, and vice versa.

We harvested more than one-third of the runoff-farmed Christmas trees at Camp Verde after only three growing seasons. All of the 75 Arizona cypress on the wax-treated sand site were cut since all but a few culls were of marketable size. Most of the remaining 45 marketable cypress and Quetta pine came from the salt-treated clay site. For some unknown reasons the Quetta pines on the sand site have done poorly. Most of the remaining trees on the clay site and some of the Quetta pines on the sand site should be harvestable in 1982, after four growing seasons. By comparison, northern grown Christmas trees commonly require seven to ten years or more to attain marketable size. Hopefully, by combining runoff farming with stump culturing (leaving a lower branch when the tree is harvested to produce another and subsequent trees) we can produce three or four marketable trees in that time.

REFERENCE:

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PERSONNEL: Dwayne H. Fink and William L. Ehrler

Table 1. Plant condition ratings for Quetta, clay and sandy sites, Camp Verde, Arizona, 1979.

Quetta, sandy site: March 1979 planting

Plant Number

Row No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	3	4	A	3	0	0	2	C	3	2	5	2	3	0	0	A	1	A	0	4	A	A	0	M	5
2	3	5	R	3	A	4	3	3	R	0	M	A	2	A	A	A	M	3	0	M	0	R	3	2	0
3	C	3	C	4	C	2	5	C	C	4	5	C	3	3	R	1	1	3	2	C	3	4	R	5	2

Quetta, clay site: March 1979 planting

Plant Number

1	3	4	C	4	3	5	C	R	4	5	C	C	5	C	3	2	3	5	5	5	2	3	R	3	R
2	4	5	5	5	3	4	4	5	5	C	5	C	5	4	C	5	C	4	4	4	3	3	4	C	C
3	3	4	C	2	5	4	C	C	5	C	2	2	2	3	C	M	C	3	3	M	3	M	2	3	C

KEY: Range: 0 to 5; 0 = dead; 5 = good plant; A = Aleppo; R = early replacement; M = missing; C = cut-off

TITLE: DEVELOPMENT OF REMOTE SENSING TECHNIQUES FOR AGRICULTURAL WATER MANAGEMENT AND CROP YIELD PREDICTION

NRP: 20760 CRIS WORK UNIT: 5510-20760-003

INTRODUCTION:

Five papers were prepared and one published dealing with the crop water stress index (CWSI). Three of these papers demonstrate how plant stress can be quantified on a variety of crops. Two papers deal with how soil moisture can be inferred from a measure of canopy temperature and the last paper deals with the relationship between the CWSI and plant water potential. The effects of canopy architecture on emitted and reflected radiation are described in two manuscripts. Another manuscript details the problems of interpreting reflectance measurements from space sensors through clear and turbid atmospheres. Also, dew and atmospheric vapor pressure are investigated in a manuscript as complicating factors in interpreting spectral radiance from crops. The use of thermal and reflected radiation, together, to describe plant growth and stress is the subject of another manuscript. A short description on the use of portable calibration sources for infrared thermometers is given.

CROP WATER STRESS INDEX:

1. Jackson, R. D. Canopy temperature and crop water stress. Advances in Irrigation, Academic Press (edited by D. I. Hillel). In press.

The use of plant temperature to infer water stress is reviewed. Early research indicated that leaf temperatures were generally warmer than the air and were not related to transpiration. Later research showed that plant temperatures could be as much as 12°C below air temperature, depending upon the vapor pressure and temperature of the air and water availability. A theoretical derivation of a crop water stress index from energy balance considerations is given. The theoretical development resolved the apparent conflict between the early and more recent work. Theory and experiment have shown that crop canopy temperatures, as measured with infrared thermometers, can be used to quantify crop water stress, and therefore are a useful tool for the timing of irrigations.

2. Idso, S. B. Foliage-air temperature differential: A key to measuring and interpreting plant water stress. (To be submitted).

A plant water stress index has recently been developed which employs a radiometric measurement of foliage temperature and a psychometric measurement of the vapor pressure deficit of the air. To utilize the index, it is necessary to know the relationship that exists between foliage-air temperature differential and air vapor pressure deficit for the plant in question when it is well watered and transpiring at the potential rate. This information is provided for 26 different species for clear sky conditions. For six of these plants, including an aquatic species, such information is also included for cloudy or shaded conditions; and two grain crops have results for both pre-heading and post-heading growth stages.

3. Pinter, P. J., Jr. Remote sensing of microclimatic stress. Book Chapter In: Biometeorology in Integrated Pest Management, Academic Press. From Symposium, "Role of Biometeorology in Integrated Pest Management," Davis, CA. July 1980. J. L. Hatfield and I. J. Thompson (eds.), Academic Press. (In press).

The role of remote sensing in the timely detection of biological and physical plant stresses is discussed. Primary emphasis is placed on the reflected solar and emitted thermal regions of the spectrum where certain meteorological events such as rainfall, snowcover and frost patterns can be directly observed with remote sensing techniques. This information can be used to guide planting operations and avoid freeze damage to crops. Along these lines, data are presented which show that the density of dew on a wheat canopy is linearly correlated with a reduction in a multispectral vegetation index commonly used to monitor green plant biomass.

Other plant stresses, such as winterkill, disease and drought, can be inferred from indirect remote sensing approaches which assess stand establishment or plant vigor. For example, observations of well-watered and water-stressed alfalfa crops show that multispectral reflected solar data are correlated with rates of canopy development and thus reflect the history of a crop's past water status. The thermal infrared, on the other hand, is more sensitive to the rates of evapotranspiration and as such provides an early indication of impending water stress and certain soil-borne root diseases. In many instances, an integrated remote sensing approach which expliots several different regions of the spectrum for specific purposes may be required to identify a target or separate an agronomic parameter from a particular plant stress.

4. Jackson, R. D. Soil moisture inferences from thermal infrared measurements of vegetation temperatures. Digest of the 1981 International Geoscience and Remote Sensing Symposium. (In press).

Remote sensing methods for the estimation of soil moisture yield direct information only for the topmost layers of soil. Reflected solar, thermal infrared, and microwave techniques are sensitive to the surface skin, from the surface to about 5 cm, and from the surface to about 10 cm, respectively. When the growth of vegetation is of major interest, soil moisture needs to be inferred at least to the depth of rooting of the plants. Since remote measurement of soil moisture is depth limited, it has been suggested that plant measurements, specifically plant temperatures, may yield information about soil moisture within the root zone. To examine this possibility, three plots of wheat, initially treated similarly, and later irrigated differently, were monitored for vegetation temperature (by infrared thermometry) and for soil water content (thrice weekly neutron moisture meter measurements). Vegetation temperatures were converted to a crop water stress index (CWSI). The CWSI was found to be a non-unique function of extractable water. The non-uniqueness was probably caused by inability to adequately specify the root zone and by the fact that plants require a recovery period (5 to 6 days for this experiment) after being stressed before normal water uptake and transpiration proceeds.

5. Reginato, R. J. 1981. A remote sensing technique for agriculture. Proc. 40th Annual Convention of National Peach Council, p. 129-138.

Plant stress can be quantified using canopy temperature as the major parameter. Recent research has shown that the two major climatic factors which must be accounted for to extend the applicability of the measurement are air temperature and the evaporative demand of the atmosphere (vapor pressure deficit). With these three factors a crop water stress index (CWSI) was developed that quantifies plant stress with a value of zero at no stress to unity at maximum stress. One of the uses of this index is its relation to extractable soil water. Data describe an inverse linear trend between the CWSI and the amount of extractable water remaining in the soil profile. Information of this nature can be used to aid in determining how much water need be applied for an irrigation.

6. Pinter, P. J., Jr. Thermal infrared techniques for assessing plant water stress. In: Irrigation Scheduling for Water and Energy Conservation in the 80's. pp. 1-9. Proc. ASAE Irrig. Sched. Conf. 1981.

Stepwise, multiple linear regression analysis established that a crop water stress index (CWSI) derived from mid-day radiant leaf temperatures, air temperatures, and vapor pressure deficits, was the most important independent variable in predicting the xylem pressure potential of cotton leaves. When the CWSI was combined with the age of the crop and the evaporative demand of the atmosphere, it was used to predict the water potential of cotton on a regular basis throughout the entire growing season. This permitted day by day monitoring of cotton plant water status which could facilitate the irrigation decision making progress without resorting to tedious physiological plant measurements.

CANOPY GEOMETRY:

7. Jackson, R. D. Interactions between canopy geometry and thermal infrared measurements. Proc. of the Intern. Colloquium on Spectral Signatures of Objects in Remote Sensing, Avignon, France, Sept., 1981. (In press).

Remotely sensed temperatures of vegetated surfaces are not only influenced by the aerial and soil environment of the plants, but also by the geometry of the canopy. For canopies with incomplete ground coverage, sunlit soil will affect the measured composite temperature directly by being much warmer than plants, and indirectly by warming the lower layers of plants. A serious problem is that of extracting plant temperatures from the composite temperatures. After plants reach a certain height canopy temperatures can usually be measured if a radiometer is held at an angle of about 30 degrees from horizontal. A far more complicated measurement is that from an aircraft where the amount of vegetation seen by a scanning radiometer is smallest directly below and increases as the view angle increases. Row orientation, solar elevation and azimuth angles, soil and plant emissivities, and soil moisture differences must be accounted for. This review covers some of the many aspects of the radiometric measurement of canopy temperatures.

8. Millard, J. P., Jackson, R. D., Goettelman, R. C., and LeRoy, M. J. Solar elevation and row direction effects on multispectral scanner data obtained over cotton. Photogram. Eng. and Remote Sensing. (Submitted)

Remote sensing of row crops poses special problems in that varying amounts of soil are seen in addition to the crop. The degree to which the soil background affects the composite scene depends upon how much soil is sunlit and how much is shaded. Thus, north-south oriented rows and eastwest oriented rows of the same crop may show different spectral properties, a result previously demonstrated with hand-held radiometers. This report presents data from an airborne scanner over two adjacent cotton fields having rows in opposite directions. The row direction and sun elevation effect was very apparent in the data.

ENVIRONMENTAL EFFECTS ON REFLECTANCE:

9. Slater, P. N., and Jackson, R. D. Transforming ground measured reflectances to radiances measured by various space sensors through clear and turbid atmospheres. Proc. of the International Colloquium on Spectral Signatures of Objects in Remote Sensing, Avignon, France, Sept. 1981. (In press).

Ground measured spectral reflectance data are useful for developing relationships between agronomic parameters and remotely sensed variables. The extension of the ground data to what would be measured from a sensor on a satellite requires accounting for atmospheric effects. The influences of clear and turbid atmospheres were simulated and their effects determined f[illegible] a soil and for stressed and non-stressed vegetation. One result indicated that a turbid atmosphere can considerably reduce our ability to discriminate between stressed and non-stressed vegetation.

10. Pinter, P. J., Jr., and Jackson, R. D. Dew and vapor pressure as complicating factors in the interpretation of spectral radiance from crops. Proc. of the 15th International Symposium on Remote Sensing of Environment. (In press).

This report examines the effect of surface dew on the spectral characteris[illegible]c of wheat in five different stages of growth and demonstrates the influence of atmospheric vapor pressure on the spectral quality of target radiance in the visible and near-IR portion of the spectrum. Data were obtained using rem[illegible]vable "dew out" shelters which prevented most nighttime dew formation on reference plots. Dew was shown to cause a significant reduction in the ratio of near-IR to red radiance (Band 7/Band 5, an index which correlates well [illegible]t green biomass levels). The relationship between dew density and the depression of Band 7/Band 5 was linear and appeared independent of phenological development. Such an effect merits important consideration when timin[illegible] aircraft and satellite overpasses to yield useful agronomic data over area[illegible] where dew is a common or intermittent phenomenon. It also appears feasible t[illegible] use multitemporal spectral observations to quantify dew formation and dissipa[illegible]tion for the prediction of dew related diseases and for energy balance studies.

We evaluated the effect of atmospheric vapor pressure on spectral reflectance by comparing soil and alfalfa target radiance values with reflectances. Although the hemispheric irradiance in Band 5 was not measurably affected by the atmospheric moisture content (as indicated by screen level psychrometric measurements), the irradiance in Band 7 decreased 10 percent with a 1.5 kPa increase in vapor pressure. Such findings have important implications for hand-held radiometry where the ratio of radiance, as opposed to reflectance, in the near-IR to visible is proposed as a shortcut to normalizing the day-to-day variability caused by different solar irradiance amounts. They also have a bearing on the interpretation of satellite and aircraft data immediately following a rainstorm.

CROP REFLECTANCE AND TEMPERATURE:

11. Jackson, R. D., and Pinter, P. J., Jr. Detection of water stress in wheat by measurement of reflected solar and emitted thermal IR radiation. Proc. of the International Colloquium on Spectral Signatures of Objects in Remote Sensing, Avignon, France, Sept. 1981. (In press).

The timely detection of the onset and degree of water stress in crops is essential for proper irrigation management. A recently proposed crop water stress index (CWSI) based on canopy temperature has potential for assessing water stress. To date, however, a quantitative relation between the CWSI and stress has not been achieved. We used a multiband reflectance radiometer to monitor green biomass in four wheat plots and thus determined, by inference, the history of water stress in wheat plots. We noted the values of the CWSI at times when the reflectance measurements indicated a slowdown in growth rate of wheat. Thus "calibrated," the CWSI can be used to predict when to irrigate and how much stress the crop had experienced before irrigation.

12. Temperature Stabilization of Infrared Thermometer Calibration Sources.

With increased use of hand-held infrared thermometers (IRT) the question arises at what rate portable field calibration sources become stabilized with ambient temperature. This experiment duplicates the transfer of a calibration source from an interior working area (26-28°C) to a typical summer field condition in SW United States (38-40°C). In practice it has been found that the IRT should be acclimated about one-half hour prior to use.

The IRT, an Everest Model 110 S/N 10114 was placed in a constant temperature room in excess of 24 hours at an average temperature of 39.5°C. It had been previously calibrated at ambient temperatures of 2.5°C, 28°C, and 40°C with an independent source temperature range of -23.5°C to 70.0°C with an accuracy of ±0.1°C. Two portable calibration sources had been stabilized in a room at 26.2°C. The sources were Everest Model 1000/C with S/N 100 having a target 6 mm thick and S/N 101, 15.5 mm thick, both 87 mm in diameter with concentric groove depths extending almost the thickness of the target. Target temperatures were sensed at the center of the target with a precision thermistor and were displayed with an LCD.

The targets warmed quickly covering 4 of the 12 degrees differential within 15 minutes and 9 of the 12 degrees in 45 minutes (Fig. 1). Thereafter the rec very slowed progressively. During the entire warming period the IRT was within 0.2°C of either target.

These data show that IRT's can be checked with the Everest calibration sour No. 1000, even under conditions of rapidly changing temperature. The gun and the sources agreed with each other to within ±0.2 C, which is quite adequate for most purposes.

SUMMARY:

A crop water stress index was evaluated for well-watered alfalfa at four lo tions in the United States. It was found that the index described the plant water stress equally well in Arizona, Kansas, Nebraska, and Minnesota. Thi demonstrates the applicability of the crop water stress index under a wide variety of environmental conditions. The index has been shown useful for quantifying crop stress for the purposes of scheduling irrigations and for predicting crop yields.

A turbid atmosphere can considerably reduce our ability to discriminate between stressed and non-stressed vegetation using a simulation of satellite derived spectral reflectance data. Ground measured data are useful for dev loping relationships between agronomic parameters and remotely sensed parameters. The extension of the ground data to what would be measured from a sensor on a satellite requires accounting for atmospheric effects. The results show that atmospheric turbidity could greatly influence our interpre tation of satellite parameters.

The applicability of portable blackbody calibration sources for field use wa demonstrated. It was shown that a commercially available unit was entirely satisfactory for routine use even when the source was subjected to an instar taneous temperature change of 14 C.

PERSONNEL: R. J. Reginato, R. D. Jackson, S. B. Idso, P. J. Pinter, Jr., M. M. Paluska, R. S. Seay, J. M. Pritchard, H. L. Mastin, L. Moore.

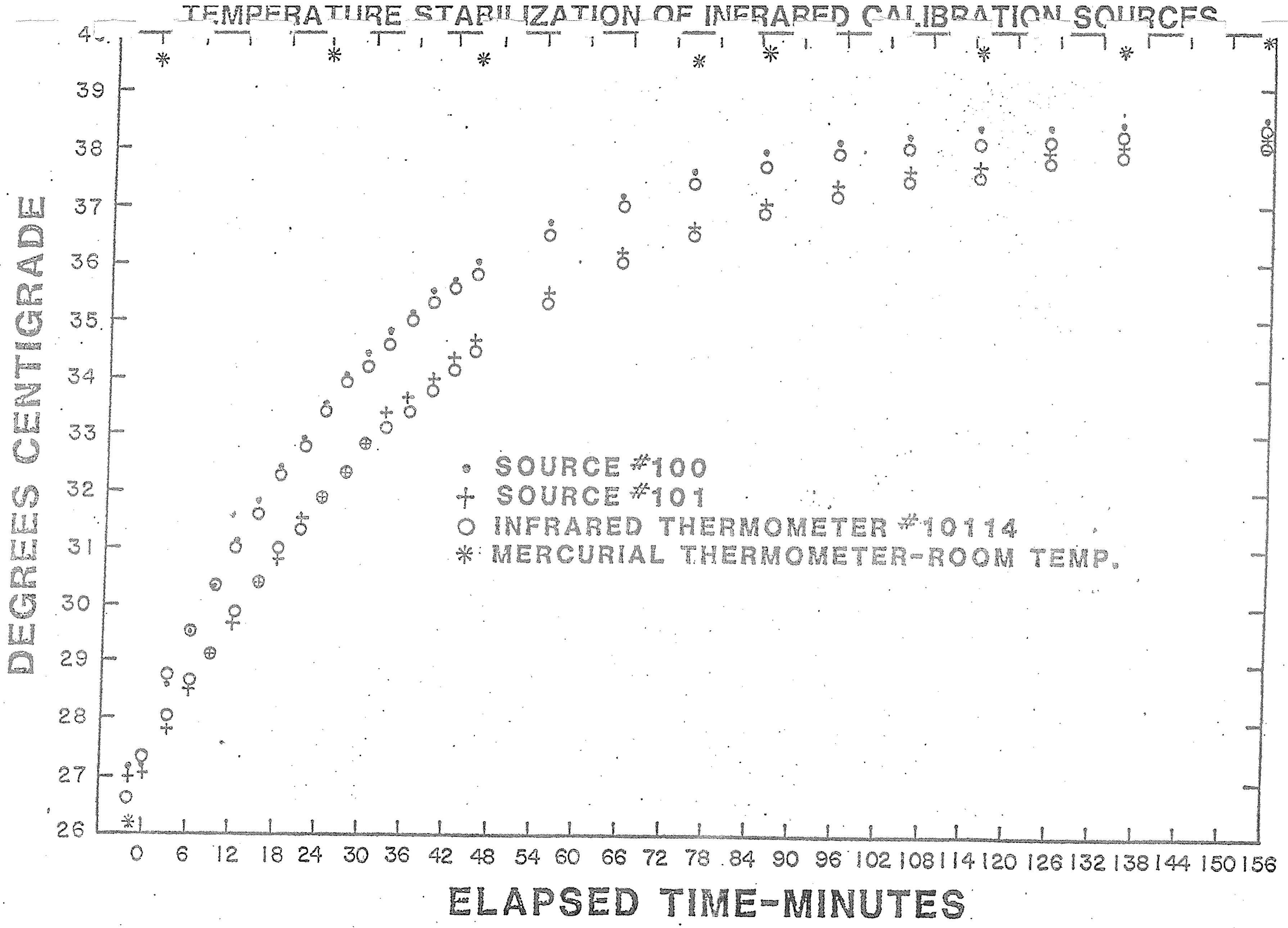

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Figure 1. Response of portable infrared calibration source and infrared thermometer to instantaneous ambient temperature change.

TITLE: CALIBRATION OF SOIL SURFACE NEUTRON MOISTURE METER

NRP: 20760 CRIS WORK UNIT: 5510-20760-003

INTRODUCTION:

Accurate information on the soil water content of both the surface and deeper layers is indispensable for reliable water management in crop production. The upper 0 to 10 cm soil layer is highly important in arid and semiarid regions, where rapid moisture changes occur soon after an irrigation or rain. This layer is of special significance for plants in their water-sensitive germinating and seedling stages. Surface soil moisture is also important in tillage, irrigation, runoff and erosion, insect breeding, and other factors which affect agricultural productivity.

Surface soil moisture measurements involve either direct soil sampling followed by gravimetric analyses or indirectly with the neutron probe technique. The former involves destructive sampling and is not very applicable where small experimental plots are involved, whereas the latter permits nondestructive repeated sampling at the same site, which is extremely useful for closely monitoring moisture changes as a function of time. The neutron scattering technique has been extensively used and much has been discussed on its theory and application (Bell, 1976, Visvalingam and Tandy, 1972). The proper calibration of the equipment is the basis for making accurate soil water content measurements. In many instances, neutron moisture meter calibration is made in the laboratory using homogeneous mixes of soil and water with careful measurement of gravimetric moisture content and bulk density; and in such cases, a linear relation with excellent correlation is shown between the volumetric water content and count rate.

Many discussions have gone on regarding the effect of water content on the sphere of influence and the effect of non-homogeneity on water content determination itself, and particularly measurements made close to the soil-atmosphere interface. Van Bavel (1961) gave such examples for his study on the influence of moisture stratification on the measured water content using the surface neutron moisture meter. The results showed a wide divergence between the actual moisture content and that estimated by the probe, and apparently such observations have discouraged extensive use of the neutron probe for measuring soil moisture content near the soil surface. However, the demonstrated effects of non-homogeneity on the neutron depth probe have not deterred its use by others, based partly on the premise that water content changes, and not necessarily the absolute water contents, are the main focus of their studies.

Several different approaches have been used to overcome difficulties in determining the moisture content at the upper soil layers, based primarily on placing additional absorber materials around the probe or on the soil surface. These include a paraffin shield (Van Bavel, 1956, Mortier et al., 1960; DeBoot, 1964), polyethylene (Pierpoint, 1966), and a Fiberglass soil tray (Eeles, 1969). A further modification by Hanna and Siam (1980) involved the use of an aluminum mesh-filled tray with turf from the vicinity of the access tubes and also a central tube to fit over the top of the access tubes.

Black and Mitchell (1968) shielded out part of the neutron source by placing a fast neutron absorber around the top of the detector tube in conjunction with a surface shield. Other special calibration techniques for this layer have also been used (Luebs, Brown and Laag, 1968; Kristensen, 1973; Grant, 1975; and Karsten and Van Der Vyver, 1979). Furthermore, some workers combined soil moisture, determined by gravimetric sampling methods in the top layers with those determined by depth probes for the remaining depths (Ackerson et al., 1977). Optimum placement of the source within the surface layer for maximizing sensitivity can be determined experimentally (Inoue, et al., 1978).

We have taken the position with the neutron equipment and especially the surface probe, that a good laboratory calibration only proves that the equipment is working properly and does not necessarily guarantee accurate moisture measurements in the field, and that reliable field measurements depends upon field calibration even though it is a time-consuming and tedious task.

Recently lightweight surface moisture probes built for testing leaks in roofs have become available. Although these were not specifically meant for soil surface moisture measurements, their design principles are similar to the early surface probe models, and they could be adapted for soil studies

The present investigation was carried out to study the possibility of using two of these types of probes for determining the moisture content of the surface layers of soil under field conditions.

MATERIALS AND METHODS:

Two types of surface neutron moisture meters specifically designed for inspecting leaks in roofs were used. These were the Neutron Surface Moisture Gauge Model 3216A, manufactured by Troxler Electronic Laboratories, Inc., and the Hydrotector Model MC-M Roof Gauge, manufactured by Campbell Pacific Nuclear Corporation. Table 1 lists some of the specifications of the two gauges, which will be referred to hereafter as (TROX) and (CPN) respectively.

Experiments were carried out in a field of Avondale loam soil at the U. S. Water Conservation Laboratory, Phoenix, Arizona. The experimental area was separated into seven plots 1.25 x 2.25 m. Irrigations of from 10 to 40 mm of water were applied to the plots to obtain a range of soil moisture contents. Count rates were taken with each surface probe as follows: five to 10 counts were recorded for both the reference standard and the actual soil surface measurement. For the TROX probe, the reference standard counts were made on four polypropylene plastic blocks 35.4 x 24.0 x 2.5 cm (length, width, and height, respectively), which was experimentally proven to be the thickness at which the count rate remained constant. The TROX equipment does not have a standard absorber block with the gauge. For the CPN probe, the reference counts were made according to the company's recommendations, by placing the gauge on the plastic block which was part of the gauge case. After the soil surface counts were recorded for each gauge, duplicate soil cores below the gauge were taken with a volumetric soil core sampler to a depth of 30 cm. The cores were sliced into 2.5-cm sections, dried at 105°C for 24 hrs for determining volumetric moisture content. The sampling sites were randomly selected for making the measurements with some sites used to develop the standard curves and others to check on the estimated water content from the standard curves.

RESULTS AND DISCUSSION:

The fractional volumetric water contents in 5 cm depth increments and the reduced count rates, R_c, (ratio of sample count rate to reference count rate) are listed in Table 2. It includes the various sampling field sites with minimal irrigation with long drying periods (Site 2) and those frequently irrigated to maintain high water content levels throughout the soil profile (Site 6). Regression equations developed for the two types of moisture probes are given in Table 3. Considering the nonlaboratory situation, good linear correlation coefficients were obtainable and which were in the same order of magnitude as the ones we have been getting for the depth probes (Nakayama and Reginato, 1982). Correlation was better for the 0 to 5 cm depth increments than for the larger increments. Multiple regression equations were also developed from the data to include the depth factor. These equations are expressed as

$$\Theta_v = -0.0588 + 0.9969\ R_c + 0.0012\ D,\ r^2 = 0.921,\ [\text{TROX}]$$

and

$$\Theta_v = -0.0454 + 0.2549\ R_c + 0.0022\ D,\ r^2 = 0.919,\ [\text{CPN}]$$

where Θ_v is the volumetric water content (cm^3/cm^3), R_c is the ratio of counts on the soil to the counts on the standard absorber material, and D is the soil depth of interest (cm) and r^2 is the coefficient to the regression equation.

Using sites other than those to get the regression equations, measured and calculated Θ_v values are compared in Table 4, where the calculated Θ_v's in Column A were derived from the equations of Table 3 and Θ_v's in Column B were from the preceding two multiple regression equations. Both treatments gave a similar range of accuracy and could complement one another.

We feel that the moisture distributions which were encountered and used to develop the calibration curve were typical of many field conditions. The artificially imposed large non-homogeneous water distribution set up in the experiments of van Bavel (1961) would very seldom represent the real situation in the field. His results, however, do demonstrate, the sampling volume of the surface probe and its relation to the surrounding moisture levels.

SUMMARY:

Two types of neutron moisture probes originally designed for detecting leaks in roofs were adapted to measure surface soil water content. These were calibrated as a function of soil water content under field conditions. Good calibration curves were obtained for both probes to a depth increment of 30 cm. This equipment can be used to monitor surface soil water content and its changes, and complements the depth probes whose accuracy fails at depths shallower than 20 cm depths.

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<u>PERSONNEL:</u> F. S. Nakayama, R. J. Reginato, S. M. Farah (visiting scientist).

Table 1. Description of surface neutron moisture probes used.

	Troxler Surface Moisture Gauge, Model 3216A (TROX)	Campbell Pacific Nuclear Model MC-M Roof Gauge (CPN)
Surface contact dimensions	22.9 x 19.0 cm	35.5 x 23.0 cm
Weight	4.0 kg	6.8 kg
Source material	$^{241}Am/Be$	$^{241}Am/Be$
Source strength	40 mCi	50 mCi
Detector	2-^{3}He tubes	2-BF_3 tubes
Count cycle	15 sec	30 sec

Table 2. Reduced count rate, R_c, for surface neutron moisture probe and volumetric soil moisture values with depth at six sites.

			Depth increment (cm)					
	TROX	CPN	0-5	5-10	10-15	15-20	20-25	25-30
Site No.	(R_c)	(R_c)	Fractional volumetric water content					
2	0.1226	0.4106	0.048	0.073	0.091	0.103	0.110	0.113
4	0.1437	0.5355	0.074	0.104	0.126	0.138	0.149	0.150
10	0.1931	0.6900	0.130	0.173	0.190	0.198	0.202	0.212
5	0.2089	0.7620	0.154	0.187	0.197	0.202	0.207	0.210
3	0.2179	0.8048	0.172	0.198	0.206	0.210	0.213	0.213
6	0.2563	0.9477	0.201	0.216	0.221	0.221	0.224	0.231

Table 3. Linear regression constants for different depth combinations for the two surface neutron moisture probes ($\Theta_v = a + bR_c$).

TROX	Constants			CPN	Constants		
Depth	a	b	r^2		a	b	r^2
0-5	-0.0953	1.182	0.9909		-0.0792	0.302	.9887
0-10	-0.0757	1.155	0.9029		-0.0405	0.288	.955
0-15	-0.0200	1.007	0.9410		-0.0063	0.257	.938
0-20	+0.0048	0.913	0.9209		+0.0171	0.234	.9202
0-25	+0.0197	0.864	0.9124		+0.0308	0.222	.917
0-30	+0.0191	0.888	0.9085		+0.0304	0.228	.906

Table 4. Measured and calculated volumetric water content for different depth increments[a/]

TROX

R_c	0-5 cm Meas	0-5 cm A	0-5 cm B	0-10 cm Meas	0-10 cm A	0-10 cm B	0-15 cm Meas	0-15 cm A	0-15 cm B
0.1381	0.051	0.068	0.090	0.083	0.099	0.101	0.106	0.119	0.112
.2139	.176	.158	.165	.197	.185	.176	.200	.196	.187
.2255	.216	.171	.177	.221	.198	.188	.220	.207	.199
.2301	.226	.177	.182	.223	.203	.193	.224	.212	.204
.2533	.226	.204	.205	.223	.229	.216	.228	.235	.227

	0-20 cm			0-25 cm			0-30 cm		
	.123	.131	.123	.138	.139	.134	.150	.142	.145
	.202	.200	.198	.204	.204	.205	.206	.209	.220
	.225	.211	.210	.227	.214	.221	.229	.219	.232
	.228	.215	.215	.231	.218	.216	.231	.223	.237
	.230	.236	.238	.232	.238	.249	.232	.244	.260

CPN

R_c	0-5 cm			0-10 cm			0-15 cm		
0.4764	0.051	0.065	0.087	0.083	0.096	0.098	0.106	0.116	0.109
.7890	.176	.160	.167	.197	.187	.178	.200	.197	.189
.8381	.216	.174	.179	.221	.201	.190	.220	.210	.201
.8499	.224	.178	.182	.223	.204	.193	.224	.213	.204
.9696	.226	.214	.213	.223	.238	.224	.228	.243	.235

	0-20 cm			0-25 cm			0-30 cm		
	.123	.128	.120	.138	.136	.131	.150	.139	.142
	.202	.202	.200	.204	.206	.211	.206	.209	.222
	.225	.213	.212	.227	.217	.223	.229	.221	.234
	.228	.216	.215	.231	.217	.226	.231	.224	.237

Average difference in water content (Calc - meas)

Depth	0-5 cm		0-10 cm		0-15 cm	
Method	A	B	A	B	A	B
TROXLER	-0.023	-0.015	-0.007	-0.015	-0.002	-0.010
CPN	-0.020	-0.013	-0.004	-0.013	0	-0.008

	0-20 cm		0-25 cm		0-30 cm	
TROXLER	-0.003	-0.005	-0.004	-0.001	-0.002	+0.009
CPN	-0.001	-0.003	-0.002	+0.003	-0.001	+0.011

[a/] Θ_v for A from individual depth functions of Table 3, and Θ_v for B from multiple regression equations that include depth function.

TITLE: EVALUATION OF CO_2-ENRICHED, UNVENTILATED, SOLAR-HEATED GREENHOUSES

NRP: 20760 CRIS WORK UNIT: 5510-20760-004

INTRODUCTION:

The benefits from growing plants in unventilated greenhouses are potentially very large. The greenhouse cover slows the loss of water, so plants can be grown in arid regions. High light intensity and long duration of sunshine in such regions are conducive to high crop yields, particularly when the greenhouses are enriched with CO_2. Therefore, this project was started with the objectives: 1. to design, test, and evaluate coolers for unventilated greenhouses under summertime conditions; 2. to design, test, and evaluate methods of solar energy storage as a means to achieve satisfactory heating in wintertime and cooling in summertime of unventilated greenhouses; 3. to evaluate the yield responses attainable with CO_2 enrichment in unventilated greenhouses; and 4. to evaluate alternative sources of CO_2 for fertilizer.

EFFECTS OF INCREASING ATMOSPHERIC CO_2 CONCENTRATION ON AGRICULTURAL PRODUCTIVITY:

A new study involved a comprehensive literature review of the effects of increasing CO_2 concentrations on the yield and water use efficiency of agricultural crops. Over 50 reports describing more than 350 experiments on 24 crops were examined. Analysis of these data indicates that a doubling of the earth's CO_2 concentration to 600 ppm (predicted for about the year 2020) will increase yields by 32% on the average, with the probable range somewhere between 20 and 46%. The review is described in the manuscript, "Man, CO_2, Climate, and Food: A Global Ecological Perspective." The review also showed that little research has been done to determine the effects of atmospheric CO_2 enrichment on productivity, water use efficiency, and photosynthesis under conditions of water and nutrient stress. Therefore, a proposal was written to conduct a major field and greenhouse experiment to obtain these important data. In addition, a prototype field CO_2 enrichment chamber was constructed for prior testing before conducting such an experiment. The chamber is described in a later section.

TOMATO YIELDS WITH CO_2 ENRICHMENT IN UNVENTILATED AND CONVENTIONAL GREENHOUSES:

Over the past 4 years, several experimental crops of tomatoes were grown in conventional, ventilated, ambient-CO_2 greenhouses in order to achieve objective 3. The results of the first two crops have been published (Kimball and Mitchell, 1979). Since then, a fall crop of 'N-65' tomatoes and a spring crop of 'Tropic' tomatoes have been grown with the same treatments. During the latter experiment, the fruits from the individual plants were weighed separately so an improved estimate of the individual plant variability was obtained. The yield results of these additional experiments are reported here.

The CO_2-enrichment - greenhouse ventilation and nutrient treatments were the same as those used with the previous winter (1977-78) crop (Kimball and Mitchell, 1979). Briefly, these were as follows: 1. A "ventilated," ambient CO_2 control greenhouse. This greenhouse was cooled with a conventional fan-pad cooling system when the greenhouse air temperature rose above 26.5 C. 2. A "ventilated," 1000 µℓ CO_2/liter greenhouse. This greenhouse was cooled like the first greenhouse, but was enriched with 1000 µℓ CO_2/liter during the daytime whenever the cooling system was off. 3. An "unventilated," 1000 µℓ CO_2/liter greenhouse. This greenhouse was equipped with a cooling system that recirculated the greenhouse air through cooled water. The cooling system came on at 26.5 C, and this greenhouse was ventilated only if the temperature rose to 29.5 C. It was enriched with 1000-µℓ CO_2/liter in the daytime when unventilated. 4. An "unventilated," 1350-µℓ CO_2/liter greenhouse. This greenhouse was like the third greenhouse, but enriched with 1350 µℓ CO_2/liter in the daytime when unventilated. The environmental conditions were monitored and were similar to those reported previously for corresponding months. All of the greenhouses were subdivided into two growing beds. The 20-plant beds on the east side of each house received standard nutrient concentrations (Fontes, 1977), whereas the 30-plant beds on the west side received 50% more concentrated solutions of all elements. The total greenhouse area per plant was 0.50 m^2, but isles and equipment access space reduced the irrigated growing area per plant to 0.35 m^2.

The fall crop of 'N-65' tomatoes, developed at the University of Hawaii, was planted in peat cubes on 11 July 1978 and transplanted into the greenhouses on 4 August 1978. The 'N-65' plants were somewhat determinate in their growth patterns, resulting in more plant variability than with 'Tropic.' The first harvest was on 29 September, and all treatments had mature fruit within 4 days of each other. Gray mold became very prevalent in the "ventilated," 1000-µℓ greenhouse in November, so the plants from this house were destroyed, and the greenhouse was fumigated. The plants in the other houses were pruned more generously than usual and then sprayed weekly with fungicide. The disease incidence in the other houses was slight, and fruit production continued until 3 January 1979.

The spring crop of 'Tropic' tomatoes was planted in peat cubes on 12 December 1978 and transplanted into the greenhouses on 12 January 1979. The plants were sprayed weekly with fungicide, and there were no apparent disease problems. The first harvest was on 9 April, and again all treatments had mature fruit within a few days of one another. The final harvest was on 21 June.

For the fall crop, the prunings and fruits from 5 randomly selected plants on the standard nutrient bed and 7 on the high nutrient bed were weighed individually to obtain an estimate of individual plant variability. For the spring crop, the prunings and fruits from all plants were weighed separately to obtain the best possible estimate of individual variability. The data were statistically analyzed following the method described by Snedecor (1956, p. 382) for a factorial arrangement of treatments with unequal numbers. Here the 4 different ventilation-CO_2 environments of the 4 greenhouses constituted 4 treatments of 1 factor, and the 2 nutrient concentrations within each greenhouse constituted 2 treatments of another factor.

The yield results are presented in Table 1. First, the mean yields of U. S. No. 1 and 2 fruit (U. S. Dept. of Agric., 1976), for the fall 'N-65' crop ranged from 6.7 kg/plant for the "ventilated," ambient CO_2 control house to 5.6 for the "unventilated," encriched houses, but the differences among treatments were not statiscally significant. These yields are about the same as those obtained from the first 3 months of harvesting of the previous winter crop (Kimball and Mitchell, 1979), and are higher than values generally reported for fall crops (Burns et al, 1976; Kretchman and Howlett, 1970; Pallas et al, 1976; Stoner, 1971). The "unventilated" houses had a higher percentage of culls, so the total fruit production and the total above-ground dry matter production were about equal for all houses. The lack of response to CO_2 enrichment for the fall crop was consistent with the previous winter month data and also with the general observation in the Northeast (Brooks et al, 1973) that fall crops generally are less responsive to CO_2 than spring crops.

The U.S. No. 1 and 2 fruit yields for the spring 'Tropic' crop ranged from 11.0 to 9.1 kg/plant (Table 1), values that are considerably higher than the 3 to 7 kg/plant reported by most workers for spring crops (Kimball and Mitchell, 1979). The first treatment comparison shows that CO_2 enrichment did not increase the yield of U. S. No. 1 and 2 fruit. However, the CO_2-enrichment treatments stimulated the production of more large fruits that were primarily U. S. No. 3 quality. Therefore, when the total fruit production or the total above-ground dry matter production is considered, the "unventilated", CO_2-enriched houses yielded about 20% more than the "ventilated," ambient CO_2 house.

The 20% increase in total fruit or dry matter production for the spring crop in the "unventilated," CO_2-enriched houses mentioned above was not as high as the 50% increase previously reported (Kimball and Mitchell, 1979). However, close comparison of the data revealed that the yields obtained in the "unventilated," CO_2-enriched houses were about the same for the different crops. Part of the reason for the lower percentage increase this time is that the "ventilated," ambient CO_2 control greenhouse had an 18% higher yield than that obtained previously.

The data in Table 1 also show that CO_2 enrichment with 1350 µℓ/liter offers no advantage over enrichment with 1000 µℓ/liter and may even be a slight detriment. The nutrient concentration data lead to a similar conclusion. The high nutrient treatments yielded significantly lower or were not significantly different from the standard nutrient treatment.

The flowers as well as the fruits produced on each individual plant were counted for the spring crop to see if the more humid environment in the "unventilated" greenhouses had any adverse effect on the percentage of fruits set. The results in Table 1 showed that there actually was a slight improvement in percent fruit set in the unventilated houses.

The fall data in Table 1 and from the previous winter crop (Kimball and Mitchell, 1979) indicate that it would be a waste of CO_2 for Phoenix growers to enrich tomato crops during the fall and winter in either "ventilated" or "unventilated" greenhouses. On the other hand, the data from spring months shows that growers with conventionally ventilated greenhouses could expect about a 5-10% increase in fruit yield from CO_2 enrichment, which would make enrichment profitable if the CO_2 were generated from natural gas (Kimball and Mitchell, 1979).

The previous report (Kimball and Mitchell, 1979) also showed that the yield increases in unventilated CO_2-enriched greenhouses probably are not consistently large enough to make an investment in the cooling tower systems like those used in these experiments profitable. Nevertheless, the very high yields show that less costly greenhouse cooling and heating systems have great potential. Such systems that incorporate solar energy storage and other innovative devices can conserve energy and water while providing this yield benefit.

MONTHLY PERFORMANCE OF GREENHOUSE HEATING AND COOLING SYSTEMS:

The first and second objectives of this project are concerned with evaluation of methods for cooling and solar heating greenhouses. The primary tool for these tasks is the MEB computer model. However, as with any such model, actual performance data are needed to validate the model and to provide values for some of the parameters. Therefore, the four test greenhouses that were used for the previous CO_2 enrichment studies were modified to represent four different heating-cooling systems.

The 27 m^2 fiberglass greenhouses have been described in previous reports. Greenhouse 3 is an unheated and uncooled control greenhouse. Greenhouse 2 is the conventional fan-pad cooled greenhouse with an electrical heater. The cooling and heating thermostats were set at 26.5°C (80 F) and 15.5°C (60 F), respectively. Greenhouse 4 is an "active" solar greenhouse. It is connected to the solar energy storge water tank described in the 1979 Annual Report. In wintertime solar energy was collected from the greenhouse whenever the greenhouse air temperature is higher than 24°C (75 F), and then when the greenhouse temperature dropped below 15.5°C (60 F) solar energy was brought back from storage. An auxiliary electric heater is in the greenhouse with its thermostat set at 13°C (55 F). In summertime solar energy was collected when the greenhouse temperature exceeded 26.5°C (80 F) and then it was dumped to a cooling tower whenever the tank temperature exceeded the outdoor wet bulb temperature by more than 2°C as determined by a differential thermostat. The air-water heat exchanger in the greenhouse and the media in the cooling tower were both wetted aspin excelsior pods, as described in the 1977 Annual Report. Greenhouse 1 is a "passive" solar greenhouse. It contains the stack of 576 one gallon plastic bottles filled with water (2.2 m^3), described in the 1980 Annual Report.

Briefly, then, the greenhouse heating and cooling types by number were:

3 - unheated and uncooled control
2 - conventional fossil fuel heat and fan-pad cooling systems
4 - "active" solar greenhouse with water tank heat storage
1 - "passive solar greenhouse with stack of water-filled bottles.

The performance data for the fist 1-3 months of operation of the greenhouses was presented in the 1980 Annual Report. During 1981, an additional 7½ months's worth of performance data were collected until 14 August when a lightning strike disabled the data logger about 6 weeks before the planned termination of the data collection. During these 7½ months, the greenhouses were vacant and no crops were grown. The soil (sand) surface was generally dry with few exceptions. One exception in all greenhouses was that the psychrometers occasionally leaked somewhat, and therefore, there often was a wet spot around the base of the tripods holding the psychrometers. Another exception was Greenhouse 4. When solar heating was operating, water evaporated from the warm heat exchanger pads and condensed on the colder roof and walls, so that at night Greenhouse 4 was much like a humid rain forest. The condensate dripped on the sand in places, but most ran down the walls and "escaped" to the outside soil around the sand beds. Thus, the sand in Greenhouse 4 was wetter than in the other greenhouses, but not so wet that drainage made it necessary to operate the sump pumps. The last exception occurred on 24 June 1981 when all the beds were flooded using hoses. The flooding was done just after a diurnal run on 23 June representative of the dry soil conditions and just before another diurnal run on 26 June representative of the wet soil conditions.

The energy use results for conventional Greenhouse 2 are presented in Figure 1. January was unusually mild and only about 5 MJ/m^2/day were required to heat the greenhouse. Toward the end of January, the heating requirement increased to about 10 and then steadily decreased until the end of April when no more heating was required. The electrical energy consumed by the evaporative cooler was about 0.1 MJ/m^2/day for most of the winter until April when it increased steadily to a maximum of about 2.5 MJ/m^2/day on about the first of June. During June, July, and August the evaporative cooler operated essentially all of the daylight hours, as evidenced by the solar closed points. They show that during the summer months essentially no solar radiation was received while the conventional greenhouse was unventilated and could have been enriched with CO_2.

The energy use results for active solar Greenhouse 4 are presented in Figure 2. Except for the middle of January when the weather was abnormally warm but cloudy, the amount of fossil energy consumed during the winter by the circulation fan and pump was generally about half that required by the heater in conventional Greenhouse 2. Once summer began the amount of fossil energy used by the circulation fan and pump plus the cooling tower fan and pump was slightly more than double that used by the evaporative cooler fan in Greenhouse 2. However, the solar collection systems of Greenhouse 4 permitted it to be closed (and enriched with CO_2) for a much larger portion of the time. The open triangles show how much solar energy was collected from the greenhouses, as measured by the temperature increase of the tank water during the day. Similarly, the closed triangles indicate how much solar energy was used for heating the greenhouse, as measured by the temperature decrease of the tank during the night.

The increased in tank temperature up through 13 April led us to think it was time to begin operating in a summer mode by turning on the cooling tower. Soon thereafter, however, cooler weather came and we had to turn the tower off on 20 April, and we left it off until 30 April. Turning the tower on, off, and on again caused a wide fluctuation in the tank temperature and thus also the scatter in the "solar collected" and "solar used" points during April and May. When in the summer mode with the cooling tower turned manually on, it was supposed to be controlled by a differential thermostat that would only let it operate when the tank temperature was 2°C warmer than the outside wet bulb. However, the controller behaved erratically and two units burned out before the problem was finally traced to faulty electrical insulation on the sensor inside the water tank. The problem was corrected on 1 June, but operation during all of May was erratic.

After the cooling tower was on most of the "solar used" energy was dumped to the atmosphere rather than actually used for heating the greenhouse. When the differential thermostat was working properly, the cooling tower ran mostly at night, but occasionally it also ran during the day. Therefore, after the summer mode started, on some days the tank temperature did not rise as much as it would have without the tower, and consequently the "solar collected" points in Figure 2 may be slightly low.

The air temperatures for Greenhouses 2 and 4 are presented in Figures 3 and 4, respectively. There is nothing particularly noteworthy here. The thermostatic control of both greenhouses generally kept the greenhouse temperature from falling much below the 15.5°C heating set point. The solar collection system cooled Greenhouse 4 close to the 26.5°C cooling set point until mid-July (Figure 2). After that time the unit opened frequently to admit outside air directly the the aspen heat exchanger pad, so additional cooling by ventilation occurred. The vent thermostat probably was switching below the 29.5°C set point. The summer maximums in Greenhouse 2 were generally higher than the set point, as would be predicted for this greenhouse when no evapotranspiration occurred in the greenhouse itself.

The air temperatures in unheated and uncooled control Greenhouse 3 and in passive solar Greenhouse 1 are presented in Figures 5 and 6, respectively. The maximum temperatures in both greenhouses were too high for most plants all year long, and the minimums were too low during the winter. The passive water storage had little effect on the greenhouse air temperatures, casting considerable doubt on the value of this type of storage for improving the temperature regime of greenhouses.

The daily water use by Greenhouses 2 and 4 is shown in Figure 7, as determined by the amount of make-up water required by the sump of Greenhouse 2 and the solar storage tank of Greenhouse 4. Greenhouse 4 used essentially no water until the start of the summer mode necessitated turning on the cooling tower. Because of the changing weather and faulty control, the water use was rather erratic. Once the cooling tower was on, the water use of the two greenhouses was roughly equivalent at about 100 mm/day during July and August.

The humidity ratios in all four greenhouses are presented in Figure 8. The most noteworthy feature is the large jump in humidity ratio on 25 June, when all the greenhouses were flooded for the diurnal run with wet soil. Several gaps in the data exist because of psychrometer malfunction. The wet bulbs seemed to only partially wet, and cursory checks indicated they were wetting properly. However, when the wicks were changed the wet bulb temperatures often dropped 5°C, so then all suspicious data points for several days prior were discarded.

The temperatures at the 0.38 m depth in the sand in each greenhouse are presented in Figure 9. This depth is the level of plastic sheet separating sand from soil. The soil temperatures at this depth are close to the mean air temperatures (Figures 3-6) for each greenhouse. During the winter they are all close to 20°C. In the summer, they rose to about 34°C in Greenhouses 1 and 3 and to about 28°C in Greenhouses 2 and 4.

DIURNAL GREENHOUSE PERFORMANCE:

The MEB computer model predicts instantaneous energy balances generally with 1 hr time steps between each individual prediction. In order to obtain data with which to rigorously test details of the model, additional diurnal measurements were made on 23 and 26 June, similar to those reported last year for 12 December. The soil surfaces were dry on 23 June, and then the beds were flooded on 24 June. After draining and equilibrating for a day, the measurements with a wet soil surface were made on 26 June. The soil moisture contents from samples taken at 1230 on 23 and 26 June are presented in Table 2.

The manual measurements consisted of using an infrared thermometer to obtain the outer cover, inner cover, wall, and soil surface temperature in each of the four greenhouses. Assmann psychrometer measurements were taken at the same time to back-up the psychrometer data recorded automatically by the data acquisition system. The water meters for the make-up water to the cooling systems for Greenhouses 2 and 4 were also read hourly. Thermocouples were installed in the roof and on the soil surface to back-up the infrared thermometers, at least during darkness. The normal measurements were taken hourly starting at 0430 hrs on both days and stopping at 2030 hrs. Taking the measurements on the half hour placed the observation time in the middle of the averaging period used by the Autodata-9 for the automatically acquired data.

The energy use results are presented in Figures 10 and 11 for conventional Greenhouse 2 and active solar Greenhouse 4, respectively. The fluxes are all about as expected, and illustrate that the solar greenhouse was closed all of these days and could have been enriched with CO_2, whereas the conventional greenhouse was ventilated for all of both days. The hourly water use by the evaporative cooler (Figure 10) and the cooling tower (Figure 11), per unit of greenhouse floor area, was converted to energy flux units, and plotted as the x's. These plots dramatically show the relatively large amount of energy handled and water consumed by these devices, and point out the need for a dry cooling device, such as a perfected night sky radiator.

The solar radiation outside, net radiation inside, and soil heat fluxes for control Greenhouse 3 and passive solar Greenhouse 1 are plotted in Figures 12 and 13. These data are as expected and are included as additional verification data for the computer model.

The temperatures of the outside air, inside air, covers, soil surfaces, and water storages are presented in Figures 14-17. Similarly, the humidity ratios of the air outside and inside the greenhouses are presented in Figures 18-21. These high quality data will provide a rigorous test for the computer model. Probably the most interesting feature is the dramatic lowering of soil surface and air temperatures in concert with the dramatic increase in humidity ratios in Greenhouses 3 and 1 when the soil was wetted between 23 and 26 June.

DEEP SOIL TEMPERATURES:

Largely in response to numerous local requests for deep soil temperature data, the deep soil temperature measurements were continued during 1981 while the automatic data logger was operating. The temperatures for 1981 are presented in Figures 18 and 19. A summary of three years' worth of data are presented in Table 3. At the 0.25 m depth the average temperature ranged from 10.8 to 37.5°C, whereas at the 2.5 m depth they ranged from 19.8 to 27.3°C. Thermal diffusivities were computed from the amplitude ratios of adjacent depths, and they averaged 0.34 mm^2/s over the whole profile.

NIGHT SKY RADIATORS:

Night sky radiators are devices that could cool a greenhouse by radiating excess daytime energy to the cold sky at night. Of particular interest to this laboratory is that they do not consume water in the cooling process. Night sky radiators with selective surfaces have been proposed by Catalanotti et al. (1975) and Bartoi et al. (1977) as a means to achieve effective natural cooling. Harrison and Walton (1978) showed that temperatures of 15°C below ambient could be achieved using commercially available white paint containing TiO_2. These authors presented detailed theoretical analyses for predicting the performance of the radiators. Briefly, they showed that an ideal night sky radiator for cooling below ambient air temperatures should be black in the 8-13 μm atmospheric window and perfectly reflective at wavelengths outside the window. This gives maximum radiating potential in the window while rejecting radiation from the air at wavelengths outside the window.

The authors mentioned above and especially Harrison (1981) also showed that the effectiveness of night sky radiators is highly dependent on atmospheric humidity. This dependence is due to the emission of radiation at wavelengths within the window from water vapor. The theoretical models presented by the previous authors can be used to predict the performance of night sky radiators, even as it varies with humidity. However, the theories require rather detailed information about the thermal radiative properties of the selective surface and the cover above it. Moreover, the authors did not provide a definition of radiator efficiency which can be used for making practical comparisons between radiators. During this past year, such a definition of efficiency was derived.

The following notation will be used:

- A area of radiator (m^2)
- C heat capacity (J/kg•K)
- F_R radiator heat removal factor identical to a solar collector heat removal factor (Duffie and Beckman, 1974, p. 146) (dimensionless)
- M mass flow rate (kg/s)
- Q rate of energy additiona to radiator from external source (W/m^2
- R thermal radiation (W/m^2)
- T temperature (K)
- $\overline{T}$ average between surface and air temperatures $[(T_m + T_a)/2]$
- U overall conduction and convection heat transfer coefficient governing the rate at which energy is transmitted through the insulating air layer and through the edges and back (W/m^2•K)
- V wind speed (m/s)
- e vapor pressure (kPa)
- f fraction of black body radiation
- m mass (kg)
- t time (s)
- δ derivative with respect to temperature
- ε emittance of radiating surface
- η efficiency of radiator
- ρ reflectance
- σ Stefan-Boltzmann constant (W/m^2•K^4)
- τ transmittance of cover
- ϕ relative humidity (%)

subscripts

- I ideal
- a air
- c cover
- f fluid
- i initial
- k known
- m mean for radiating surface
- n net
- o outside 8-14μ atmospheric window
- s radiating surface
- v vertical
- w within 8-14 μ atmospheric window
- x unknown
- 1 inlet
- 2 outlet

<u>Prediction of Surface Temperatures</u>. The type of night sky radiator to be considered is very similar to a solar collector. It consists of a radiating surface with a heat transfer fluid in intimate thermal contact with the surface. The fluid supplies the energy which the user wishes to dump to the atmosphere or outer space. Above the radiating surface is a cover that ideally is transparent to thermal radiation, and which provides an insulating air layer to permit the radiator to operate at temperatures several degrees below ambient air temperature. The rate of energy addition per unit area to such a radiator from an external source, Q (W/m^2) can be determined from careful measurements of the fluid flow rate, M, inlet fluid temperature, T_1, outlet fluid temperature, T_2. The rate is given by:

$$Q = MC\,(T_1 - T_2)/A \qquad (1)$$

The rate can also be expressed as a balance of energy on the surface of the radiator.

$$Q + R_{aw}\beta_{aw} + R_{ao}\beta_{ao} + R_{sw}\beta_{sw} + R_{so}\beta_{so} + R_{cw}\beta_{cw} + R_{co}\beta_{co} + H(T_a - T_s) = 0 \qquad (2$$

where: $\beta_{aw} = \tau_{cw}\ \varepsilon_{sw}/(1 - \rho_{sw}\rho_{cw})$

$\beta_{ao} = \tau_{co}\ \varepsilon_{so}/(1 - \rho_{so}\rho_{co})$

$\beta_{sw} = [\rho_{cw}\ \varepsilon_{sw}/(1 - \rho_{sw}\rho_{cw})] - 1$

$\beta_{so} = [\rho_{co}\ \varepsilon_{so}/(1 - \rho_{so}\rho_{co})] - 1$

$\beta_{cw} = \varepsilon_{sw}/(1 - \rho_{sw}\rho_{cw})$

$\beta_{co} = \varepsilon_{so}/(1 - \rho_{so}\rho_{co})$

The sky radiation inside and outside the atmospheric window is defined by

$$R_{aw} = \varepsilon_{ao}\ f_{aw}\ \sigma T_a^{\ 4} \qquad R_{ao} = \varepsilon_{ao}\ f_{ao}\ \sigma T_a^{\ 4} \qquad (3)$$

where the emittance inside the window, ε_{aw}, can be computed from (Idso, 1981) for clear skies

$$\varepsilon_{awv} = 0.24 + 2.98 \times 10^{-6}\ e_a^{\ 2} \exp\ (3000/(T_a + 273.16)) \qquad (4)$$

$$\varepsilon_{aw} = \varepsilon_{awv}\ (1.4 - 0.4\ \varepsilon_{awv})$$

The sky is assumed to be black outside the window so that $\varepsilon_{ao} = 1.0$.

The fraction of radiation within the 8-14 μ band can be computed for any given temperature (in degree C) from

$$f_w = 0.34906 + 1.2495E{-}3 * T - 0.91397E{-}5T^2 \qquad (5)$$

Within the 10-40C temperature range, f_w changes only slightly (Figure 24). The fraction of radiation outside the window, $f_o = 1 - f_w$.

The cover is assumed to be at air temperature because convection above the cover should be relatively great compared to the stagnant air under the cover (Catalanotti et al., 1975). Then the radiation emitted by the cover can be computed from known emittances of the cover

$$R_{cw} = \varepsilon_{cw}\ f_{aw}\ \sigma T_a^{\ 4} \qquad R_{co} = \varepsilon_{co}\ f_{ao}\ \sigma T_a^{\ 4} \qquad (6)$$

The radiation emitted from the surface could be computed from the surface temperature, if it were known. Generally, it is an unknown, but Equation 2 can be solved to obtain the surface temperature. The surface radiation is defined as:

$$R_{sw} = \varepsilon_{sw}\ f_{sw}\ \sigma Ts^4 \text{ and } R_{so}\ \varepsilon_{so}\ f_{so}\ \sigma T_s^{\ 4}$$

The temperature can be linearized following Kimball (1981).

Let $\delta_{sw} = 4\varepsilon_{sw} f_{sw} \sigma (T_s^o)^3$ and $\delta_{so} = 4\varepsilon_{so} f_{so} \sigma (T_s^o)^3$ (7)

where T_s^o is an "old" estimate of T_s.

Then $R_{sw} = R_{sw}^o + \delta_{sw} (T_s - T_s^o)$ and $R_{so} = R_{so}^o + \delta_{so} (T_s - T_s^o)$ (8)

Letting $Y_{sw} = R_{sw}^o - \delta_{sw} T_s^o$ and $Y_{so} = R_{so}^o - \delta_{sw} T_s^o$ (9)

Equation 2 can be solved to obtain T_s explicitly.

$$T_s = \frac{-\beta_{sw}Y_{sw} - \beta_{so}Y_{so} - R_{aw}\beta_{aw} - R_{ao}\beta_{ao} - R_{cw}\beta_{cw} - R_{co}\beta_{co} - UT_a - Q}{\beta_{sw}\delta_{sw} + \beta_{so}\delta_{so} - U} \quad (10)$$

A good radiator will radiate much more energy to the sky than it receives, and therefore the net radiation above the radiator is an indicator of radiator performance. Defining R_n as upward-downward radiation.

$$\begin{aligned} R_n = {} & R_{sw}[\tau_{cw}/(1 - \rho_{cw}\rho_{sw})] \\ & + R_{so}[\tau_{co}/(1 - \rho_{co}\rho_{so})] \\ & + R_{cw}[1 + (\rho_{cw}\tau_{cw}/(1 - \rho_{cw}\rho_{sw}))] \\ & + R_{co}[1 + (\rho_{co}\tau_{co}/(1 - \rho_{co}\rho_{so}))] \\ & - R_{aw}[1 - \rho_{cw} - (\rho_{sw}\tau_{cw}^2/(1 - \rho_{cw}\rho_{sw}))] \\ & - R_{ao}[1 - \rho_{co} - (\rho_{so}\tau_{co}^2/(1 - \rho_{co}\rho_{so}))] \end{aligned} \quad (11)$$

Normalizing the performance of night sky radiators. The performance of a night sky radiator can be normalized with respect to a "perfect radiator." The cover of such a radiator would be perfectly transparent so that $\tau_{cw} = \tau_{co} = 1$, $\varepsilon_{cw} = \varepsilon_{co} = 0$, and $\rho_{cw} = \rho_{co} = 0$. Furthermore it would be perfectly insulated so that $U = 0$. The surface of this ideal radiator would be highly reflective outside the atmosphere window but black inside the window so that $\rho_{so} = 1$, $\rho_{sw} = 0$, $\varepsilon_{so} = 0$, and $\varepsilon_{sw} = 1$. Substituting these values into equation 2,

$$Q + R_{aw} - R_{sw} = 0$$

or

$$Q + \varepsilon_{aw} f_w \delta T_a^4 - f_w \delta T_s^4 = 0$$

If energy is supplied to the plate at a rate such that the plate temperature equals air temperature then

$$Q = f_w(1 - \varepsilon_{aw}) \delta T_a^4 \quad (12)$$

This rate of energy addition is dependent only on the atmosphere, and therefore we can define

$$R_I = f_w (1 - \varepsilon_{aw}) \delta T_a^4 \qquad (13)$$

to be the power at which the atmosphere can receive energy from an ideal radiator. R_I is plotted as function of temperature and vapor pressure in Figure 26. For typical operating conditions of T_a = 20C and e_a = 1 kPa, R_I = 91 W/m^2.

This ideal radiator power is a useful parameter for standardizing night sky radiator tests performed under different conditions, as can be seen from the following. Ignoring reflections and absorption by the cover, Equation 2 can be written

$$Q - (\varepsilon_{sw} f_w + \varepsilon_{so} f_o) \delta T_s^4 + (\varepsilon_{aw} \varepsilon_{sw} f_w + \varepsilon_{ao} \varepsilon_{so} f_o) \delta T_a^4 + U(T_a - T_s) = 0 \qquad (14)$$

Rearranging

$$Q = -f_w \varepsilon_{sw} (\varepsilon_{aw} \delta T_a^4 - \delta T_s^4) - f_o \varepsilon_{so} (\varepsilon_{ao} T_a^4 - \delta T_s^4) - U (T_a - T_s)$$

Noting that $\varepsilon_{ao} \approx 1$, approximating $\delta T_a^4 - \delta T_s^4$ with $4\delta\bar{T}^3 (T_a - T_s)$, and dividing by R_I yields:

$$Q/R_I = \varepsilon_{sw} - [4\delta\bar{T}_3 (f_w \varepsilon_{sw} + f_o \varepsilon_{so}) + U][(T_a - T_s)/R_I] \qquad (15)$$

and when Q = 0,

$$T_a - T_s = R_I \varepsilon_{sw}/[4\delta\bar{T}_3 (f_w \varepsilon_{sw} + f_o \varepsilon_{so}) + U] \qquad (16)$$

Equation 15 defines a line with an intercept of ε_{sw} and a slope of $[4\delta T_3 (f_w \varepsilon_{sw} + f_o \varepsilon_{so} + U)]$. The intercept is an "efficiency" of the radiator when $T_s = T_a$ and it depends on the surface properties, not on the atmospheric conditions of the test. It is analogous to the way the performance of solar collectors is normalized by dividing by the intensity of solar radiation (Beckman et al., 1977). The slope is only weakly dependent on air temperature ($4\delta T^3$ is plotted in Figure 24), enabling the maximum temperature depression of the plate temperature below air temperature (when Q = 0) to be predicted from Equation 15. In practice, the effect of absorption and reflections by the cover degrade the performance predicted by Equations 14 and 15. However, if Q/R_I is plotted against $(T_a - T_m)/R_I$, the curves obtained by powerful radiators should be above those of less powerful radiators, even though the tests may have been performed under somewhat different sky conditions. Moreover, the curves are nearly linear.

Measurements of night sky radiator performance. To obtain actual measurements of the radiating power of night sky radiators, two night sky radiators were constructed. They were constructed from 1/2 copper tubes connected to form serpetines with 6 extruded aluminum fin plates snapped over the copper tubes, such as are used for solar collectors. The length of each fin was 96.6 cm and the six fins side by side had a width of 83.8 cm to give an area of 0.810 m^2 for each radiator. These aluminum radiating surfaces were suspended in wooden boxes with 2.5 inches of styrofoam and 4 inches of fiberglass on the bottom. Polyethylene was used for the cover across the top of the boxes. It was held level about 2 cm above the radiating surface, by three monofilament nylon lines stretched across from side to side of the boxes.

One of the radiators was painted with a white paint high in T_iO_2 as described by Harrison and Walton (1978) to try to produce a surface which is nearly reflective outside the window. A later report by Michell and Biggs (1979) indicates such paint is nearly black throughout the thermal IR spectrum. Nonetheless, the paint used was Pratt & Lambert "effecto enamel white E1173." All of the pigment was T_iO_2 Type III. Pigment composed 31.3% of the weight and the remaining 68.7% was vehicle: -31.9% soya-alkyd resin, 0.3% non-volatile drier, and 36.5% petroleum distillate.

Two runs were made to measure the overall heat gain coefficient, U, using The method of Catalanotti et al. (1975). If the aluminum fins are cooled for below the equilibrium radiating temperature at night and then allowed to warm to this equilibrium temperature, the rate of temperature rise can be described by:

$$(m_k C_k + m_x C_x) \frac{dT_m}{dt} = UA(T_a - T_m) + \tau R_a A - R_s A \qquad (17)$$

where $m_k C_k$ are the known mass and heat capacity of the aluminum, copper, and fluid, and $m_x C_x$ are the unkown mass and heat capacity of the wood, insulation, etc. By using a radiator with a polished aluminum surface, the last two radiation terms are made relatively small and (17) can be solved to yield.

$$\ln[(T_a - T_m)/(T_{ai} - T_{mi})] = - [UA/(m_k C_k + m_x (_x] \; t \qquad (18)$$

By making runs with two known masses, two equations with two unknown (U and $m_x C_x$) are obtained, which can then be solved. On the night of 31 July 81, ice was added to the water reservoir and the resultant cold water was circulated through the polished aluminum radiator. After an hour, a second run was made with additional aluminum plates under the fins. A similar run was made on the night of 4 Aug 81 with extra plates and on 5 Aug 81 with no extra plates. The logarithm of the ratio of the air-surface temperature to the initial air-surface temperature was plotted against time for each run and the slopes of the lines were measured.

The results of the U factor measurements are presented in Table 4. On 31 July 81 the wind blew higher than normal and the U factor was correspondingly large. Smaller values were measured on the 4 and 5 Augst 1981 runs. The computed values of the unknown heat capacitance of the wood and insulation seem unrealistically high. Recomputation of U assuming the $m_x C_x = 0$, yielded about half the size obtained from the simultaneous equations.

A second approach to measuring the overall heat gain coefficient, U, was also investigated. Approximating the radiation terms in Equation 2 with the net radiation (Equation 11)

$$Q = R_n - U\,(T_a - T_m) \qquad (19)$$

where R_n is the net radiation above the plate. On the nights of 22, 23, and 24 May measurements were taken of the net radiations using two Fritchen-type net radiometers positioned 10 cm above the center of each radiator. On these nights no fluid was pumped through the radiators, so Q = 0 and $U \cong R_n/(T_a - T_m)$. The average of all the U values for the calmer nights is about 2.7 $W/m^2 \cdot C$.

Measurements were also made of the performance of the two radiators on selected clear nights during 1981, and these results are presented in Table 5. On 23-25, the water flow rate was zero, so Q = 0 and the aluminum and white paint surfaces cooled to about 3 and 8 C, respectively, below air temperature. Later, on other dates warm water was flowing at the rates listed in the table. Concurrent mesurements were made of T_1 and T_2 to determine Q from Equation 1. However, the T_1 and T_2 evidently were not measured with enough accuracy and precision and the resultant Q's were very erratic and often very unrealistic. Therefore for those nights when water was flowing through the radiators, Q was approximated using the net radiation measurement above the cover in Equation 19.

The values of Q/R_I from Table 5 are plotted against $(T_a - T_s)/R_I$ in Figure 26. As expected from Equation 14, the data for the "white" paint form a nearly linear curve. The aluminum data are more scattered but are also linear. Also shown in Figure 26 are several theoretical curves computed from Equations 2-10. The aluminum data are above their theoretical line, but the emittance of the aluminum might have been 0.2 instead of the 0.1 used in the computations, so this discrepancy can be explained. The "white" paint data are below the lines for both white and black paint. However, the measured U was estimated using the net radiation, so this may explain why they are below the theoretical curves.

Some general observations about the relative power of various night sky radiators can be made by inspecting Figure 26. First, the normalization procedure using R_I is effective because the differences due to changing atmospheric conditions are made small relative to the differences between the various radiators. The dashed lines shown in Figure 26 indicate the change in normalized curve for black paint going from cold, dry (0 C, 0.1 kPa) conditions to hot, humid (50 C, 4 kPa) conditions. The change in $(T_a - T_s)/R_I$ at Q = 0 was about 34% whereas the change in $T_a - T_s$ was about 87% (8.9 C to 3.5 C). More dramatically, the change in Q/R_I at $T_a - T_s$ is zero, whereas the variation in Q alone could be from 165 to 0 W/m^2 (Figure 26).

It can be also seen from Figure 26 that the actual radiators are pedicted to achieve considerably smaller maximum depressions than their ideal counterparts. Also a truly selective white paint isn't much better than black paint until the surface has cooled several degrees below air temperature. Figure 26 also illustrates rather dramatically that the greatest power can be achieved operating a black radiator without a cover at temperatures above air temperature. Unfortunately, during the hottest months when cooling is desired it may not be possible to operate above air temperatures, so large areas of covered surface may be required, depending on the application.

Figure 27 is an interesting presentation of conflicting data and theories. The Harrison and Walton (1978) data point was published first for a night sky radiator with white paint having high TiO_2 content. They claimed it had an emittance of 0.92 in the atmospheric window and 0.05 outside the window. Then, in 1981 Harrison published a mass of data outlined by the wavy line in Figure 27. The single data point published earlier by Harrison and Walton is considerably above these data. He also presented a theory of operation for the radiator taking into account absorption by water vapor at various angles and elevations in the sky. He said he used the paint properties presented earlier by Harrison and Walton. Obviously his theoretical curves agree nicely with his data in Figure 27. Meanwhile, Michell and Biggs (1979) published a reflectance spectrum for high TiO_2 paint which showed the paint to be quite black throughout the thermal IR spectrum with an emittance of about 0.92 outside the atmospheric window, rather than the 0.05 claimed earlier by Harrison and Walton. If Harrison indeed used an emittance of 0.05 for his theoretical curves while his radiator actually had an emittance of 0.92, the agreement between his curves and data casts considerable doubt on this theory.

Also shown in Figure 27 are the theoretical curves computed from Equations 2-10. The agreement betwen the black paint curve (since Michell and Biggs indicate the white TiO_2 paint is really black) and the points measured in this study is fair and the aluminum points agree with the aluminum curve. However these theoretical curves conflict dramatically with both the data and the theoretical curves of Harrison. Even the shape of the curves is different. The shape of the curves from this study is determined by the shape of the Idso (1981) sky emittance (Equation 4). Obviously there is qualitative difference between this equation and the method used by Harrison. While, Harrison's curves are suspect due to the surface emittance problem, one cannot so easily discredit his data. They indicate that the temprature depression (T_a - T_s) decreases much faster with increasing vapor pressure than predicted by the theory presented here.

In view of all the conflicts presented in Figure 27, it has been decided to obtain more night sky radiation this year, particularly when the summer monsoon brings higher vapor pressures. Many more points with Q = 0 and with positive, precisely-measured Q provided by electrical heating will be obtained. Data from additional radiators painted with flat black will also be obtained for comparison with the white paint and aluminum radiators.

A PROTOTYPE FIELD CO_2 ENRICHMENT CHAMBER:

..s mentioned previously, a prototype field CO_2 enrichment chamber was constructed and is being tested for possible use in a major enrichment xperiment. The design is similar to that of Heagle et al. (1973), in that .t has transparent plastic sides and an open top. A fan provides continuous ventilation with enriched air through perforated tubes all around the bottom perimeter. Unlike the circular shape of Heagle et al., however, his chamber is square in order to fit into row crops like cotton more easily. The square shape is also compatible with polylock, a commerically-available aluminum extrusion, to easily fasten the transparent plastic to he frame.

The chamber is 120 inches (3.05 m) long on each side in order to accommodate hree standard 40 inch rows, and it is 2.07 m high for an area of 9.29 m^2 nd a volume of 19.2 m^3. Following Heagle et al., the ventilation rate was selected to be 4 air changes per minute, or 1.28 m^3/s (2720 CFM), for an average vertical velocity of 14 cm/s. Under full sun (1000 W/m^2) this ventilation rate will give a temperature rise of about 6.5 C if there were no evapotranspiration. If half of the incoming energy is dissipated as latent energy (evapotranspiration = 0.74 mm/hr), then the temperature rise would e 3.2 C. An evapotranspiration rate of 0.74 mm/hr would increase the umidity ratio of the air by 1.4 g H_2O/kg air and the vapor pressure by 0.21 kPa. These temperature increases are definitely higher than desirable. "owever, the alternative of refrigerating totally enclosed chambers is not esirable either.

The chamber was constructed from an angle aluminum frame with angle iron round an access door and around the top perimeter. A door and a top cover ..as constructed from Al with magnetic refrigerator door gaskets bolted around each. These gaskets provide a good seal, yet allow the door and over to be quickly removed and replaced. During normal operation the door ould be on and the cover off. The cover would be set in place quickly, and ventilation and CO_2 enrichment ceased in order to make photosynthesis determinations by measuring the transient decrease in CO_2 concentration in he chamber. The walls were constructed from clear PVC film stretched between pieces of polylock. A piece of polylock was bolted all around the chamber at the 1 m height. The upper wall was a single layer of PVC film. he lower was two thickness to form a tube. On the side opposite the door, fan was mounted to inject air into the tube. The inner wall was then perforated to permit air to enter the chamber.

he fan selected was a Dayton 20 in, 3-speed fan rated at 3425 (hi), 3000 (med), and 2340 (lo) CFM free air delivery. Measurements were made with a hot wire anemometer of the velocity of air flow out the holes for two hole ensities and fan rates. These data are presented in Table 7. Later a perforated cover was stretched across the top of the chamber and additional flow measurements are taken. However, the anemometer was malfunctioning, o the later data were invalid. Measurements were taken of the air temerature difference between inside and out and solar radiation, so the ventilation rate was estimated from these data assuming the total heat load "as 90% of the solar load. It appears from these data that using a tube all with 162 28-mm-dia holes and a cover with 46 47-mm-dia holes at a medium fan speed will produce the desired 4 air changes per minute.

The yields of a fall (1978) crop of tomatoes (Lycopersicon esculentum Mill. cv. N-65) and of a spring (1979) crop (cv. Tropic) from CO_2-enriched, unventilated and conventionally ventilated greenhouses were analyzed. The ventilated, ambient CO_2 greenhouse had U. S. No. 1 and 2 fruit yields of 6.19 and 10.4 kg/plant for the fall and spring crops, respectively. For the fall crop, there were no significant differences in yield among the greenhouses. For the spring crop, the total fruit yield was 20% higher in the unventilated, CO_2-enriched greenhouse. However, CO_2 enrichment stimulated production of large, catfaced U. S. No. 3 fruits, so there was little difference in U. S. No. 1 and 2 fruit yield among the greenhouses. There was no significant yield difference between an unventilated greenhouse enriched with 1000 µℓ CO_2/liter and another enriched with 1350 µℓ/liter. There also was no yield improvement obtained from using nutrient concentrations 50% higher than standard in any of the greenhouses for either crop. Fruit set of the spring crop was not significantly affected by the higher humidity in the unventilated greenhouses.

Air temperatures, energy consumption, and water use were measured with four test greenhouses: 1 - a passive solar greenhouse with a stock of water-filled bottles, 2 - a conventional greenhour with a fossil fuel heater and fan-pad evaporative cooling system, 3 - an unheated and uncooled control, and 4 - an active solar greenhouse with water tank heat storage. The amount of fossil energy required to operate the pumps and fans for heating the active solar greenhouse was about half the 10 MJ/m^2/day used by the heater of the conventional greenhouse. During the summer the active solar greenhouse used about double the 5 MJ/m^2/day for cooling the conventional greenhouse. However, the active solar greenhouse was closed and could have been enriched with CO_2 for almost all year until mid-July, whereas the conventional was ventilated much of the time starting in mid-April.

The temperatures in the conventional and the active solar greenhouse were generally well within the range of optimum plant growth. The temperatures in the passive solar greenhouse were generally too hot in the daytime all year long and too cold at night in winter for optimum plant growth. The maximums were only about 2 C cooler in the passive solar house than the 30-60 C maximums in the uncooled house. Similarly, the minimums were only about 2 C warmer than the 2-28 C of the unheated-uncooled house. Apparently the rate of heat transfer between the bottles and the air was simply too slow for effective temperature control in the passive solar house.

Intensive measurements of wall and soil surface temperatures of all four greenhouses were also made on two diurnal runs, one with a dry soil surface and another when it was wet. The primary objective of these diurnal measurements and of the annual performance measurements was to obtain simultaneous data for four very different greenhouse types for comparison with hourly, daily, and annual computer model predictions. The validated greenhouse model will be used to evaluate the feasibility of using closed greenhouses in arid environments to grow crops with little water. It can also be used to size components for optimal design of solar heating systems.

Additional tests were made on the uniformity and distribution of CO_2 in the enrichment chamber. Twenty small tygon tubes were suspended from lines stretched across the chamber in the grid pattern shown in Figure 28. CO_2 from a tank was injected just behind the fan, as indicated on the figure. At first the CO_2 supply line merely terminated, and then certain positions near the fan had very high concentrations. Then a manifold with many small holes was coiled behind the fan and this promoted much better mixing with the entering air. The coefficient of variation was still about 10%, so another tactic was tried to reduce the variation still further. Davis and Rogers (1980) found that a chamber with a nozzle top had much less concentration variation then a simple open-top chamber. It is also logical that if the area for flow out the top is reduced, then the average upward velocity will be higher. Therefore, there would be less possibility for wind currents to reverse the flow and mix unenriched air into the chamber. Because only rather tall crops would receive direct sun most of the time in such chambers anyway, it was decided to cover the chamber with a perforated cover in spite of the slight reduction in solar radiation.

The CO_2 distribution results with two covers having 50 and 180 47-mm-diameter holes are presented in Table 8. During these tests CO_2 was injected at an unmeasured rate of approximately 48 l/min. The control value was not moved from run to run, so the injection rate should have been constant. Some particularly high concentrations occurred at positions 14-19 on 3 Feb. and some rather low ones at positions 16-20 on 2 Mar. Since the extremes occurred at the same positions in sampling sequence, it seems more likely that the flow rate was changing than that the CO_2 enrichment chamber with the perforated top wasn't producing uniform CO_2 concentrations. More studies with a metered flow with and without the perforated cover are planned.

Additional tests were made to determine the suitability of chambers for photosynthetic measurements. The PVC film cover with the magnetic gasket was attached to the top angle iron frame. Then CO_2 was injected into the chamber and its decrease with time was determined by periodic sampling. Then $\ln[C - C_o)/(C_i - C_o)]$ was plotted against time in hours and the slope measured to obtain the number of air changes per hour. When the chamber was indoors with stagnant air inside, the leakage rate was 0.06 changes per hour. An oscillating fan was then placed inside which gave an average air velocity of 0.62 m/s as measured at 9 positions with a hot wire anemometer. The leakage rate increased to 0.24 changes per hour. Additional tests were conducted outside on 29 and 30 Dec 81, when the wind speed averaged 1.2 m/s on both days. The leakage rate on both days was 0.35 changes per hour. A leakage rate of 0.35 changes per hour will cause about a 1% error in a photosynthetsis measurement after 1.7 minutes if no corrections were made, so it appears that the chamber can be sealed well enough to be a photosynthesis measurement chamber as well as a CO_2 enrichment chamber.

SUMMARY AND CONCLUSIONS

A comprehensive literature review of more than 350 experiments on 24 crops indicates that a doubling of the earth's CO_2 concentration will increase yields an average of 32%.

A theory for predicting the performance of night sky radiators was developed. Two night sky radiators were bult, one with a T_1O_2 white paint surface, reported to be selective for the night sky, and the other with aluminum. Numerous measurements of radiating power from the change in temperature of water flowing through the radiators were attempted, but the temperature change could not be measured precisely enough. Three data points obtained when no water was flowing had fair agreement with theory. A comparison with previous theories and data from the literature showed large conflicts and inconsistencies. Additional data from radiators whose external power is supplied from precisely measured electrical heaters is planned for next year.

A research proposal to study the "Effects of Atmospheric CO_2 Enrichment on Productivity, Water Use Efficiency, and Photsynthesis of Crop Plants under Water and Nutrient Stress" was prepared. A portion of that proposal plans to utilize open-top chambers to provide a field plot with a controlled CO_2 enrichment. A prototype chamber was built which featured transparent plastic film stretched over an angle aluminum and and iron frame. Magnetic gaskets permit quick attachment of a door and cover to the angle iron frame for photosynthesis measurements. Preliminary testing indicated that it will be possible to achieve good distribution and uniformity of CO_2 concentrations under normal operating conditions and that adequate sealing can be attained for photosynthesis measurements.

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<u>:RSONNEL:</u> B. A. Kimball, S. T. Mitchell, and G. B. Brooks.

Table 1: Summary of the analyses of variance of the yields of two tomato crops grown in "ventilated" (V) and "unventilated" (U) greenhouses at various CO_2 enrichments ($\mu\ell/\ell$) and at standard and high nutrient concentrations. No interactions were significant.

	TREATMENTS									
	Ventilation-CO_2						Nutr. Conc.			
	Means[z]						Means[z]			
ITEM	V ambient	V 1000	U 1000	U 1350	LSD[y]	Significance[x]	St'd	High	LSD[y]	Significance[x]
Fall 1978 'N-65' tomato crop:										
U. S. No. 1 and 2 fruit yield (kg/plant)	6.7a	-	5.6a	5.6a	-	NS	6.4a	5.6a	-	NS
	% dif[w]	-	-16	-16						
Percent U. S. 3 plus culls (kg x 100/kg total)	11	-	18	21			16	17		
	% dif[w]		+64	+91						
U. S. No. 1 and 2 fruit size (g/fruit)	167	-	149	153			162	161		
	% dif[w]	-	-11	-8						
Above-ground dry matter (kg/plant)	1.12	-	1.06	1.08			1.16	1.01		
	% dif[w]		-5	-4						
Spring 1979 'Tropic' tomato crop:										
U. S. No. 1 and 2 fruit yield (kg/plant)	10.4ab	9.8bc	11.0a	9.1c	0.9	**	10.9a	9.5b	0.6	**
	% dif[w]	-6	+6	-13						
Total fruit yield (kg/plant)	12.2c	12.8c	15.2a	14.0b	0.8	**	14.8a	12.7b	0.6	**
	% dif[w]	+6	+25	+15						
Percent U. S. No. 3 (kg x 100/kg total)	14.9d	22.7c	27.6b	35.2a	4.4	**	25.6a	25.2a	-	NS
	% dif[w]	+52	+85	+136						
U. S. No. 1 and 2 fruit size (g/fruit)	229b	225b	260a	256a	13	**	254a	236a	-	NS
	% dif[w]	-2	+14	+12						

Table 1 (Cont)

ITEM		TREATMENTS: Ventilation-CO_2, Means[z]: V ambient	V 1000	U 1000	U 1350	LSD[y]	Significance[x]	Nutr. Conc., Means[z]: St'd	High	LSD[y]	Significance[x]
Above-ground dry matter (kg/plant)		1.59c	1.67c	1.91a	1.79b	0.09	**	1.89a	1.65b	0.07	**
	% dif[w]		+5	+20	+13						
Percent fruit set (No. fruits x 100/no. flowers)		68.3b	65.7b	73.7a	69.5ab	4.4	**	70.3a	68.8a	-	NS
	% dif[w]		-4	+8	+2						

z Means not followed by the same letter are significantly different at 5%.
y Least significant difference at 5% after F test, following Carmer and Swanson (3).
x NS implies not significantly different at 5%. ** indicates significant difference at 1%.
w % difference is the percentage change of the mean for the CO_2-enriched houses with respect to the ventilated, ambient CO_2 greenhouse.

Table 2: Moisture content (% dry weight) of the sand in the east and west beds of the four greenhouses sampled at 1230 on 23 and 26 June 1981.

	Greenhouse Number							
	1		2		3		4	
depth	east	west	east	west	east	west	east	west
cm	- - - - - - - -			Wt. %	- - - - - - - -			
23 June 1981:								
0 - 1	0.20	0.80	0.25	0.37	0.09	0.26	0.34	0.47
1 - 3	0.22	1.03	0.40	0.84	0.14	0.24	0.36	0.68
3 - 10	0.38	4.51	4.32	4.85	0.20	3.67	0.85	3.22
19 - 38	0.66	5.84	4.08	6.16	0.24	1.04	1.88	4.56
26 June 1981:								
0 - 1	9.6	14.4	20.6	17.0	12.8	11.1	15.5	15.6
1 - 3	10.4	10.7	17.9	19.0	12.8	9.1	20.4	20.2
3 - 10	14.2	17.3	15.8	15.2	16.0	16.0	14.5	13.4
10 - 38	16.4	19.3	19.7	19.6	30.2	11.8	17.2	19.0

Table 3. Summary of deep soil temperature data for bare Avondale loam in Phoenix, Arizona. (From B. A. Kimball, S. T. Mitchell, and G. Brooks, U. S. Water Conservation Laboratory 1981 Annual Report).

	Depth (m)											
	0.25		0.5		1.0		1.5		2.0		2.5	
Item/Year	Temp (C)	Date	Temp (C)	Date	Temp (C)	Date	Temp (C)	Date	Temp (C)	Date	Temp (C)	Date
Maximums:												
1978	38	10Aug	35	20Aug	33	25Aug	31	01Sep	30	05Oct	28	05Oct
1979	37.8	10Aug	34.5	10Aug	32.0	10Aug	29.5	15Aug	28.0	25Sep	26.8	20Oct
1981	36.8	12Jul	35.0	15Jul	32.2	25Jul	32.2	26Jul	--	-	27.2?	05Aug?
Avg.	37.5		34.8		32.4		30.0		29.0		27.3	
Minimums:												
1979	9.0	1Feb	10.6	20Jan	14.3	05Feb	16.2	10Feb	18.2	25Feb	18.8	20Mar
1981	12.5	6Feb	14.0	05Feb	16.3	15Feb	18.0	21Feb	--	--	20.8	02Apr
Avg.	10.8		12.3		15.3		17.1		18.2		19.8	
Average Maximum - Average Minimum:												
	26.7		22.5		17.1		13.8		10.8		7.5	
Thermal Diffusivity[z] (mm^2/s):												
		0.21		0.33		0.54		0.41		0.19		

[z] $D_T = (\omega/2)\,[(z_2 - z_1)/\ln(A_1/A_2)]^2$, where $z_2 - z_1$ is the difference in depth (adjacent were used), A_1/A_2 is the ratio of the (maximums - minimums) between the two depths, and ω is the annual frequency (rad/s) = $2\pi/(3600 \times 24 \times 365)$. The average thermal diffusivity for the profiles is 0.34 mm^2/s.

Table 4. Summary of U factor determinations for night sky radiator. The values determined using the net radiation, R_n, are averages over 8 hours.

Date	m_kC_k (J/C)	Slope (sec^{-1})	m_xC_x (J/C)	U ($W/m^2\,°C$)	U if $m_xC_x = 0$ ($W/m^2\,°C$)	Avg. Wind (m/s)
Using rate of change of polished aluminum radiator temperature:						
31 Jul 81	8165	2.69×10^{-4}	12841	7.0	2.7	2.5
31 Jul 81	11307	2.34×10^{-4}			3.3	2.5
4 Aug 81	16130	0.72×10^{-4}	7334	2.1	1.4	1.[illegible]
5 Aug 81	8165	1.09×10^{-4}			1.1	0.5
Using $U = R_n/(T_a - T_m)$ when the flow rate was zero:						
For alumimum radiator:						
22-23 May					4.1	0.7
23-24 May					3.4	1.[illegible]
24-25 May					4.5	1.[illegible]
For white paint radiator:						
22-23 May					2.4	0.7
23-24 May					2.3	1.0
24-25 May					2.6	1.[illegible]
Average of all values except 31 July					2.7	

Table 5. Summary of night sky radiator performances during 1981. The values are averages over the first five hours of each day.

Date	Air Temp	Vap. Press. e_a	Wind Speed V	Ideal Loss[4/] R_I	Flow Rate M	T_m[2/]	$T_a - T_m$	R_n	Q[1/]	η[3/]	$\frac{T_a - T_m}{R_I}$
						Bare Aluminum					
	(C)	(kPa)	(m/s)	(W/m^2)	kg/s	(C)	(C)	(W/m^2)	(W/m^2)		
23 May	21.2	0.88	0.7	97	0.0	17.4	3.8	14.8	0	0	0.039
24 May	19.5	0.91	1.1	93	0.0	17.6	1.9	20.9	0	0	0.020
25 May	22.4	1.07	1.0	93	0.0	18.6	3.8	15.3	0	0	0.041
10 Sep	25.6	1.62	1.4	79	0.10	31.5	-5.9	40.4	56	0.71	-.075
11 Sep	23.8	1.65	1.4	75	0.10	30.7	-6.9	41.1	60	0.80	-.092
12 Sep	23.6	1.51	0.9	80	0.10	30.6	-7.0	41.7	61	0.76	-.088
17 Sep	24.4	1.45	2.3	82	0.023	30.0	-5.6	41.0	56	0.68	-.068
18 Sep	28.0	1.46	2.8	95	0.023	31.6	-3.6	44.7	54	0.57	-.038
19 Sep	23.7	1.65	2.0	75	0.017	29.8	-6.1	34.9	51	0.68	-.081
20 Sep	24.1	1.65	1.5	76	0.017	31.2	-7.1	35.6	55	0.72	-.093
6 Oct	17.7	1.39	0.5	74	0.022	24.9	-7.2	32.1	52	0.70	-.097
7 Oct	19.6	1.31	0.8	80	0.25	27.8	-8.2	30.3	52	0.65	-.103
						White Paint					
23 May						13.6	7.6	19.5	0	0	0.078
24 May						11.8	7.7	28.4	0	0	0.083
25 May						14.2	8.2	21.1	0	0	0.088
10 Sep						32.0	-6.4	47.5	65	0.82	-.081
11 Sep						31.4	-7.6	53.2	74	0.99	-.101
12 Sep						30.1	-6.5	49.7	67	0.84	-.081
17 Sep						29.8	-5.4	44.0	59	0.72	-.066
18 Sep						31.2	-3.2	43.2	52	0.55	-.034
19 Sep						29.1	-5.4	38.9	54	0.72	-.072
20 Sep						29.4	-5.3	38.9	53	0.70	-.070
6 Oct						25.4	-7.7	52.0	73	0.99	-.104
7 Oct						26.9	-7.3	48.0	68	0.85	-.091

1/ Computed from $Q = R_n - U\,(T_a - T_m)$ with $U = 2.7$ W/m^2·C for the dates when the flow rate was greater than zero.

2/ fin 3 temperatures.

3/ Efficiency, $\eta = Q/R_I$

4/ $R_I = f_w\,(1 - \varepsilon_{aw})\,\sigma\,T_a^4$

Table 6. Values of radiative properties of the night sky radiators used to compute the curves in Figure 27.

Parameter	Ideal Selec.	Ideal Black	Alum.	White Paint	Black Paint Cover	Black Paint No-Cover
ε_{sw} 8-14 μ window surface emittance	1	1	0.10[1/]	0.92[2/]	0.95[3/]	0.95[3/]
ε_{so} outside window surface emittance	0	1	0.10[1/]	0.05[2/]	0.95[3/]	0.95[3/]
τ_{cw} 8-14 μ cover transmittance	1	1	0.80[4/]	0.80[4/]	0.80[4/]	1
τ_{co} outside cover transmittance	1	1	0.80[4/]	0.80[4/]	0.80[4/]	1
ε_{co} 8-14 μ cover emittance	0	0	0.10[4/]	0.10[4/]	0.10[4/]	0
ε_{co} outside cover emittance	0	0	0.10[4/]	0.10[4/]	0.10[4/]	0
U convection-conduction heat transfer coefficient	1.5[5/]	1.5[5/]	2.7[6/]	2.7[6/]	2.7[6/]	9.5[7/]

1/ From Duffie and Beckman (1974, p. 97).
2/ From Harrison and Walton (1977).
3/ Estimated.
4/ From Catalanotti et al. (1975) for polyethylene.
5/ From ASHRAE (1972, p.358) for the conductance of a stagnant, 19-mm-thick, low emittance air space with downward heat flow.
6/ Average measurement from Table 4.
7/ From the McAdams expression, U = 5.7 + 3.8 V (m/s), for a 1 m/s wind (Duffie and Beckman, 1974, p. 83).

Table 7. Summary of air flow measurements for prototype CO_2 enrichment chamber.

Date	No. of Holes: Wall[1/]	No. of Holes: Cover[2/]	Fan Speed	Avg. Velocity[3/] ± Std. Dev. (m/s)	Solar Radiation (W/m^2)	$T_{ai} - T_{ao}$ (C)	Air Changes per Minute
4 Nov 81	87	open	med	3.12	-		2.1
4 Nov 81	87	open	high	4.86 ± .57	-		3.2
5 Nov 81	162	open	med	2.96 ± 0.33	-		3.7
5 Nov 81	162	open	high	4.00 ± .41	-		4.9
2 Feb 82	162	46	med	-	674	4.0	3.9
2 Feb 82	162	46	high	-	648	1.6	9.4
2 Feb 82	162	180	med	-	-	-	-
2 Feb 82	162	180	high	-	-	-	-

1/ Hole diameter = 28 mm.

2/ Hole diameter = 47 mm.

3/ Velocity through wall holes when the cover was off and through the cover holes when it was on.

Table 8. CO_2 concentrations at 20 positions in the CO_2 enrichment chamber and their average, standard deviation, and coefficient of variation for several uniformity tests under the conditions indicated.

Date:	5 Feb 82	3 Feb 82	25 Feb 82	25 Feb 82	26 Feb 82	26 Feb 82	2 Mar 82	2 Mar 82
Wind Speed (m/s):	1.6	1.6	0.5	0.5	2.3	1.3	0.9	0.6
No. Holes in Cover:	50	50	50	50	180	180	180	180
Fan Speed:	Med	High	High	Med	Med	High	Med	High
Sample Height (m):	0.3	0.3	1.0	1.0	1.0	1.0	0.3	0.3
Position No:	[CO_2 concentration (ppm)]							
1	712	943	1232	1061	1272	1146	1299	1123
2	1459	1152	1114	1191	1385	1168	1583	1160
3	1144	1080	1092	1448	862	1057	1416	1421
4	948	1125	1108	1422	905	1004	1130	1021
5	873	1454	1008	1067	901	1089	632	1172
6	1067	1188	1108	1473	1282	1107	644	1081
7	1029	966	1041	1012	1121	1047	1396	841
8	1070	1310	1112	1183	1290	1109	1516	813
9	1429	1244	1034	1294	843	1053	593	920
10	1243	2020	1215	1043	950	1130	1449	796
11	905	1096	1275	1520	1241	1148	1569	945
12	1294	2175	990	1072	999	884	1720	892
13	990	1109	1231	1376	1090	923	1643	1454
14	1576	1728	1331	1799	1683	1145	1694	1349
15	1419	2028	1386	1450	1792	1588	1370	1168
16	1168	1885	1017	1401	1452	1459	626	1238
17	1470	2029	1183	1701	1439	1087	615	1676
18	1151	2001	1464	1215	1599	1230	576	1672
19	781	2125	1128	1193	1234	1265	569	1621
20	1144	1050	1180	1114	820	790	561	879
Average:	1144	1485	1162	1302	1205	1121	1130	1162
Std. Dev:	242	451	129	224	294	178	462	288
Coef. Var. (%):	21	30	11	17	24	16	41	25

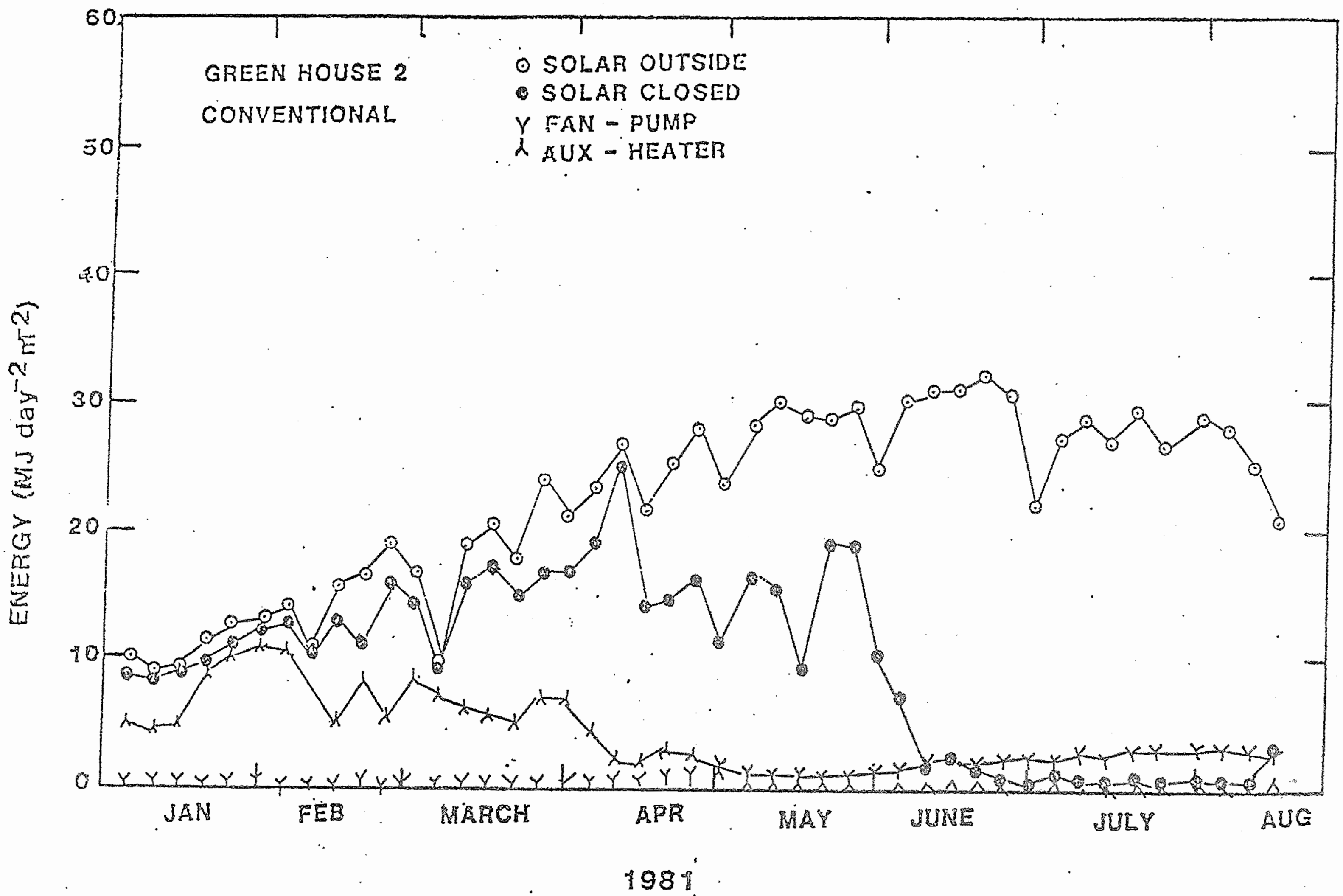


Figure 1. Energy use in conventional Greenhouse 2 in 1981. Each point is a 5 day average. The solar closed points are the amounts of solar energy received while the greenhouse was not ventilated and could have been enriched with CO_2.

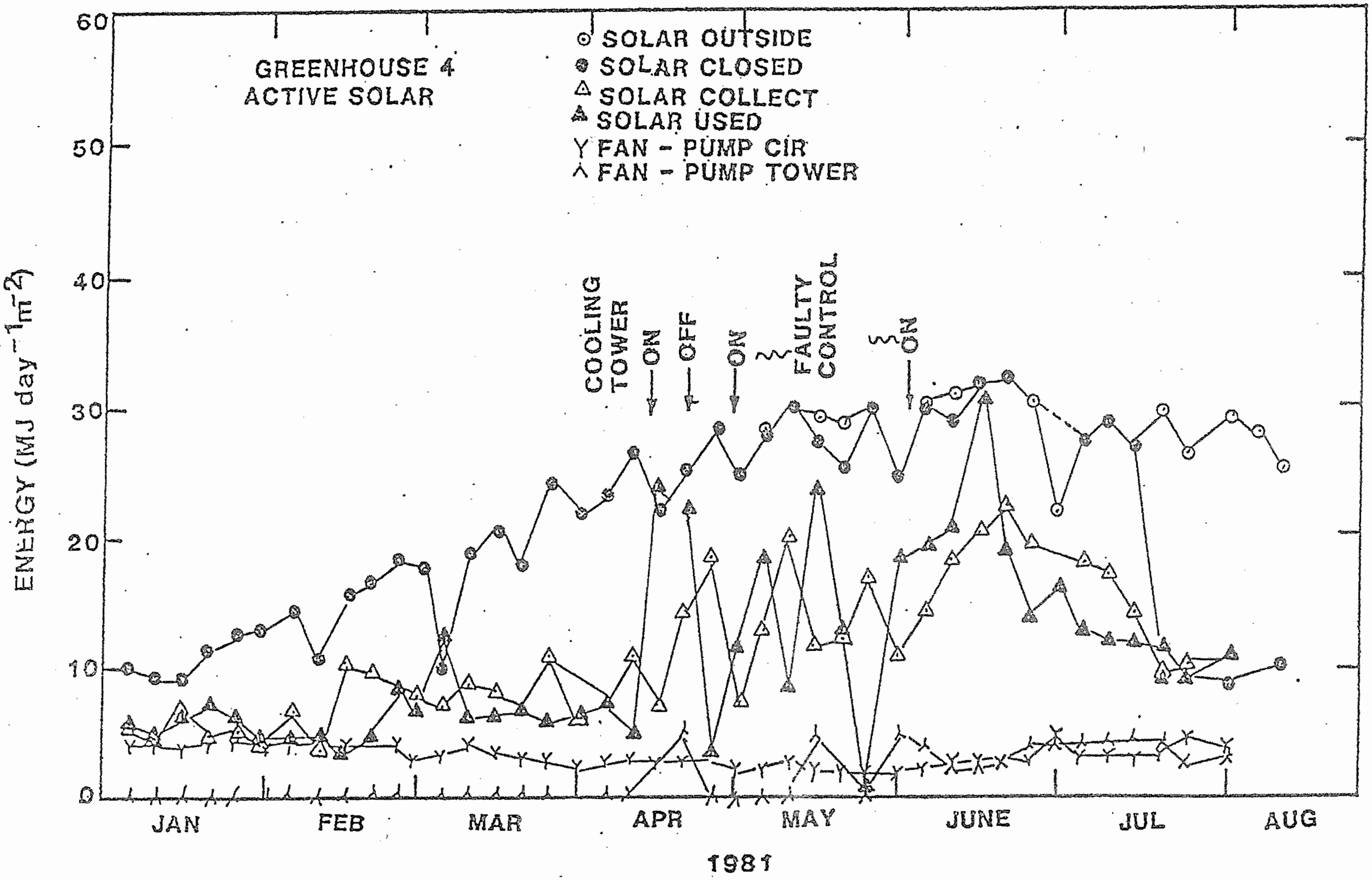


Figure 2. Energy use in "active" solar Greenhouse 4 in 1981. Each point is a 5 day average. The greenhouse did not require ventilation until mid-May, so most of the "solar outside" points are superimposed [illegible] the [illegible]ola[illegible]cei[illegible] wh[illegible] closed' points.

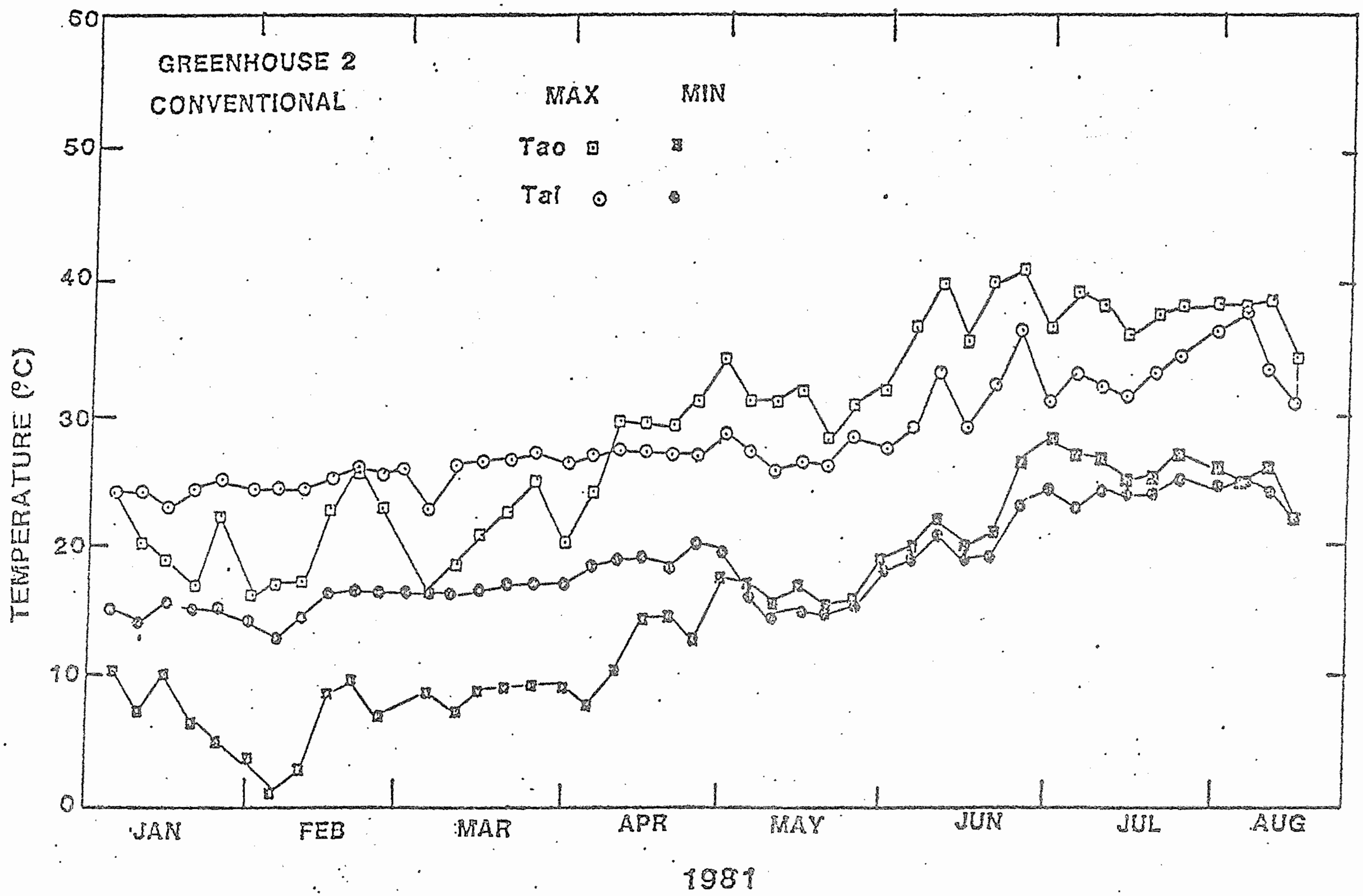


Figure 3. Maxium and minimum air temperature inside Conventional Greenhouse 2 (Tai) and outside (Tao) during 1981. Each point is a 5 day average.

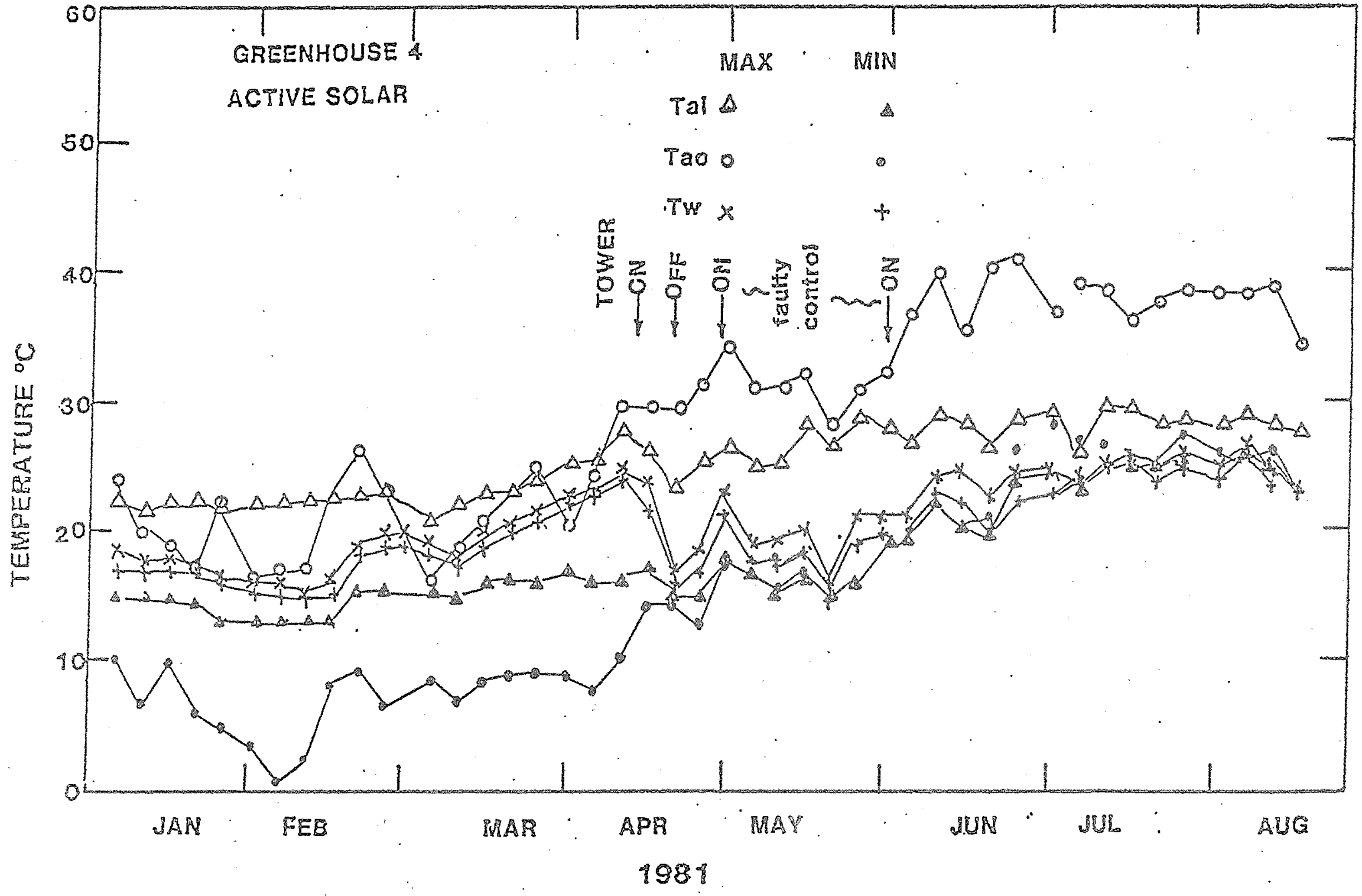


Figure 4. Maximum and minimum temperatures inside active solar Greenhouse 4 (Tai), outside (Tao), and of the storage water (Tw) during 1981. Each point is a 5 day ...age

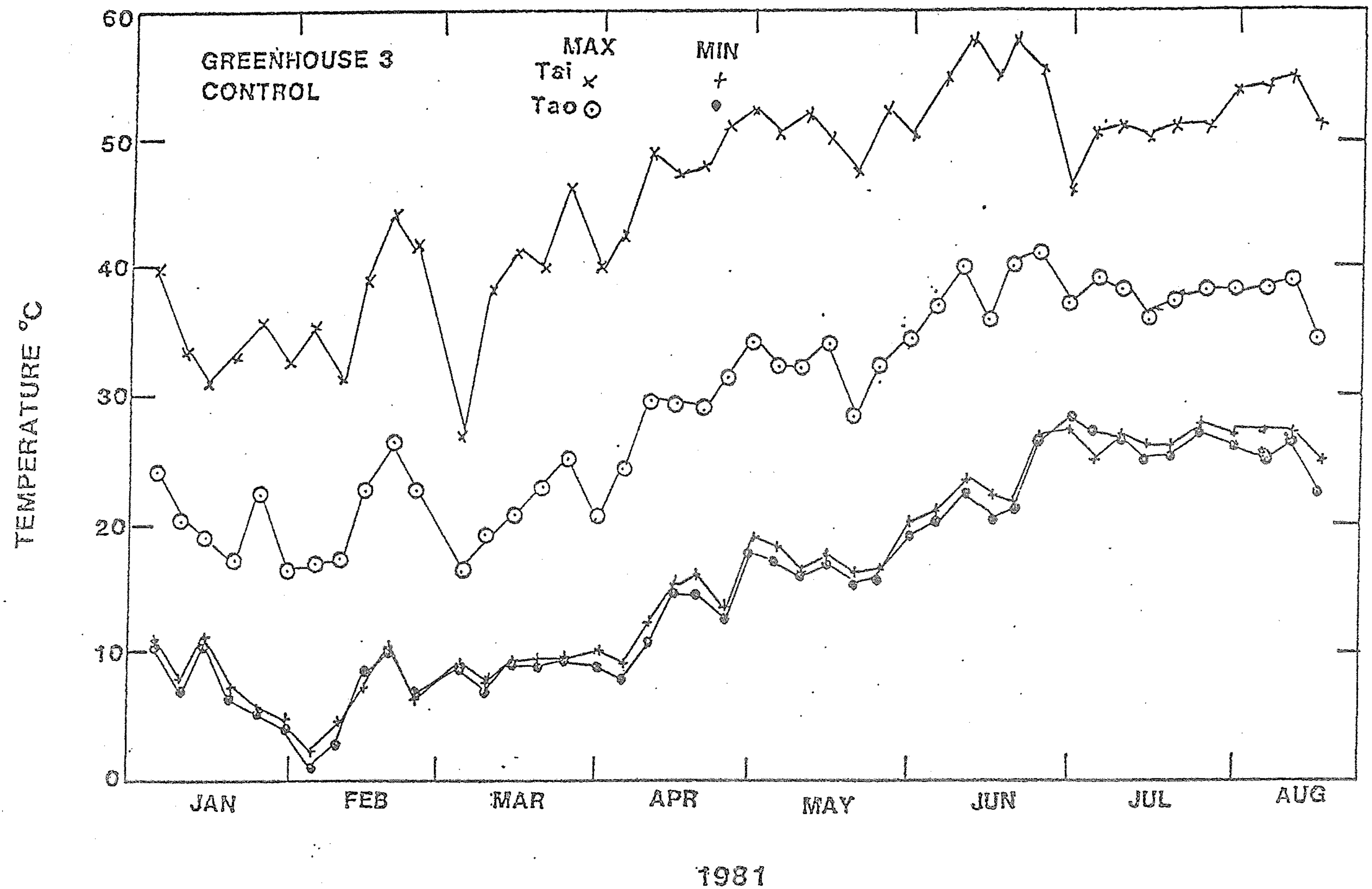


Figure 5. Maximum and mimimum air temperature inside unheated and uncooled Greenhouse 3 (Tai) and outside (Tao) during 1981. Each point is a 5 day average.

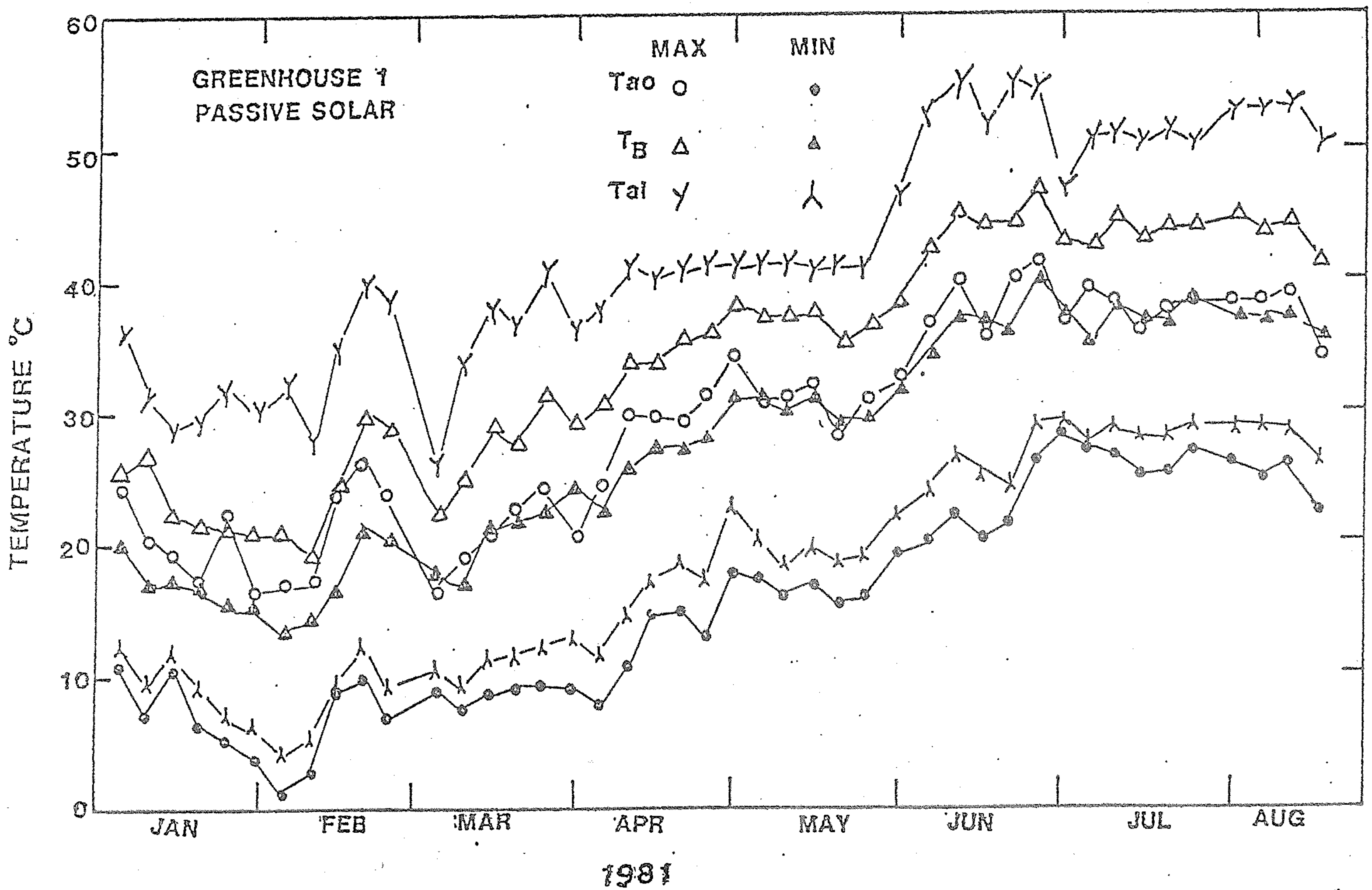


Figure 6. Maximum and minimum air temperature inside passive solar Greenhouse 1 (Tai) and outside (Tao) and of the storage bottles (T_B) during 1981. Each point is a 5 day average.

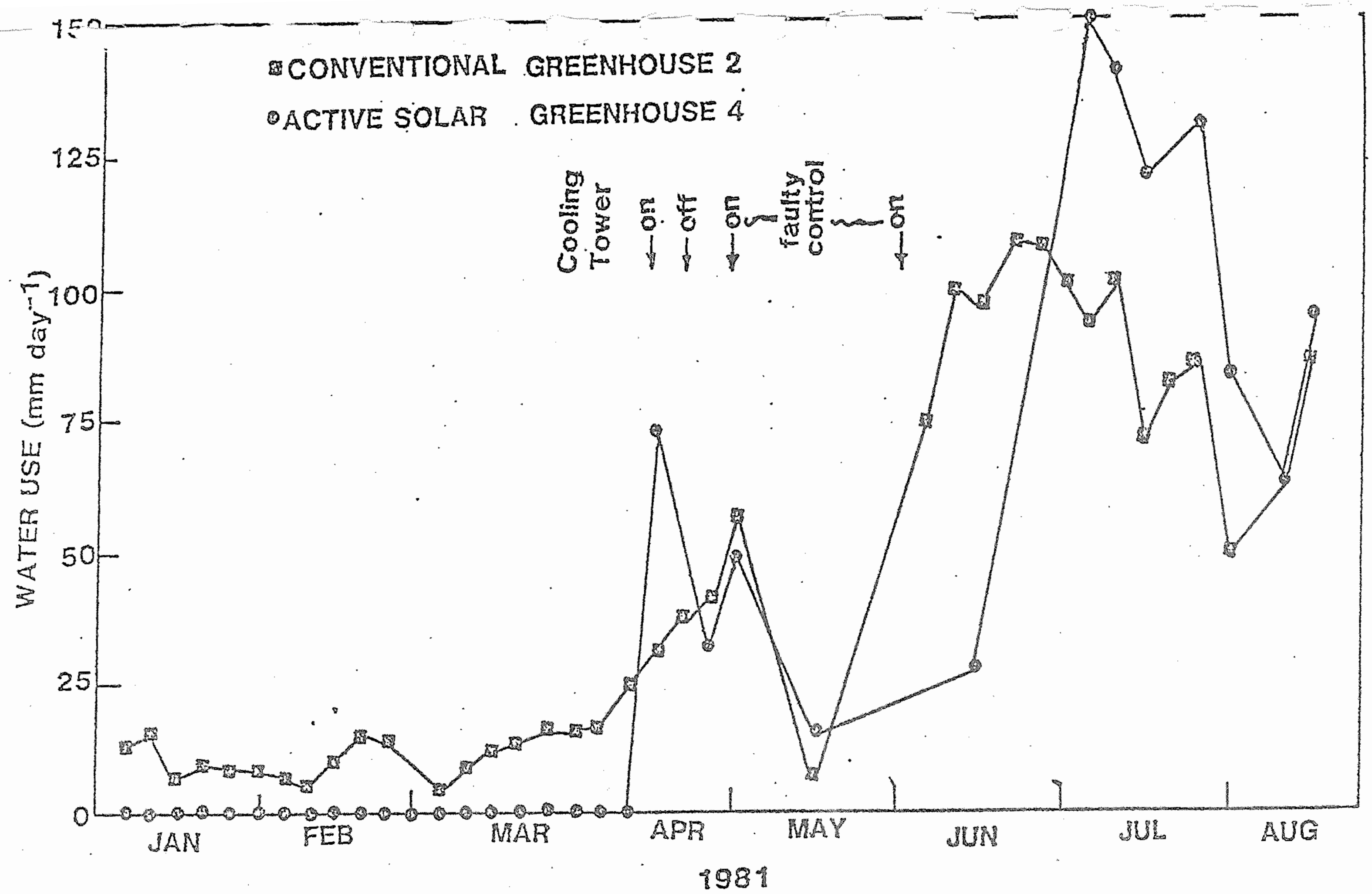


Figure 7. Water use by Greenhouses 2 and 4 during 1981. Each point is an average of 5 or more days.

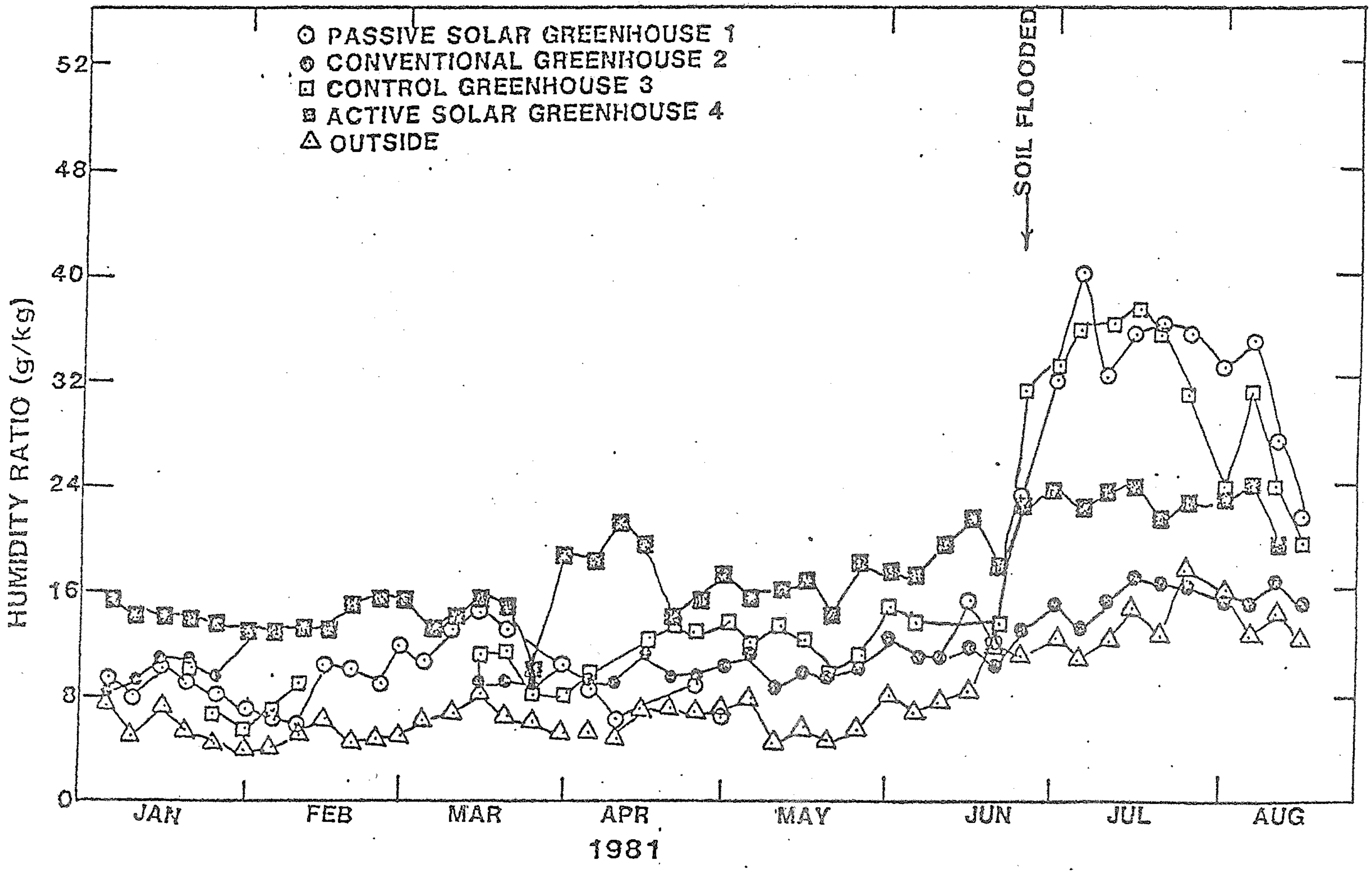


Figure 8. Noon humidity ratios inside the four greenhouses as well as the average daily outside humidity ratio. The points are [illegible] day average.

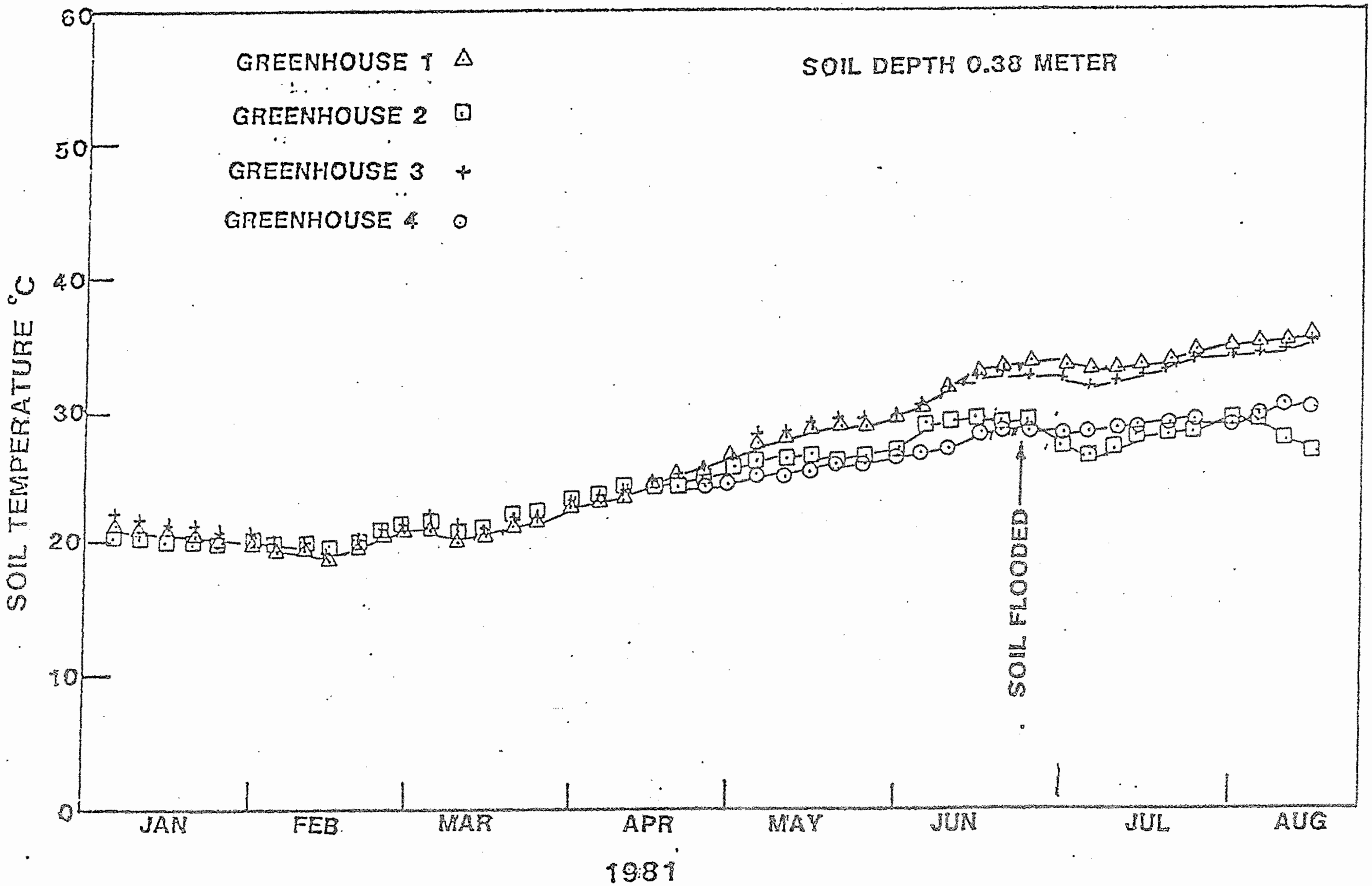


Figure 9. Noon soil temperature at the 0.38 meter depth in the sand beneath each greenhouse during 1981. The points are 5 day average.

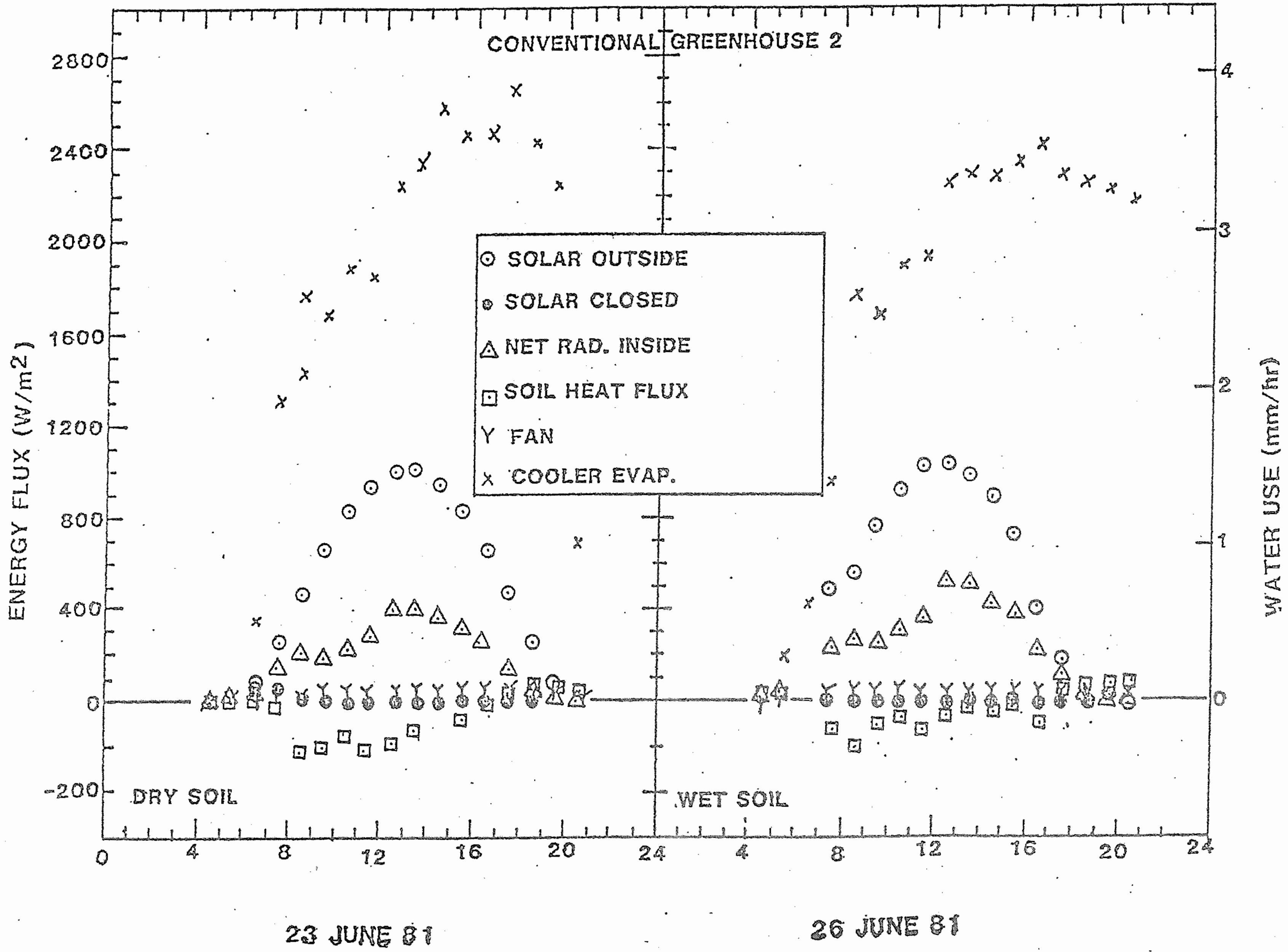


Figure 10. Energy fluxes in conventional Greenhouses 2 on 23 and 26 June 1981 when the soil was dry and wet, respectively. The fluxes [illegible] radiation, outside sol[illegible] recorded [illegible] the greenhouse was closed (and [illegible]

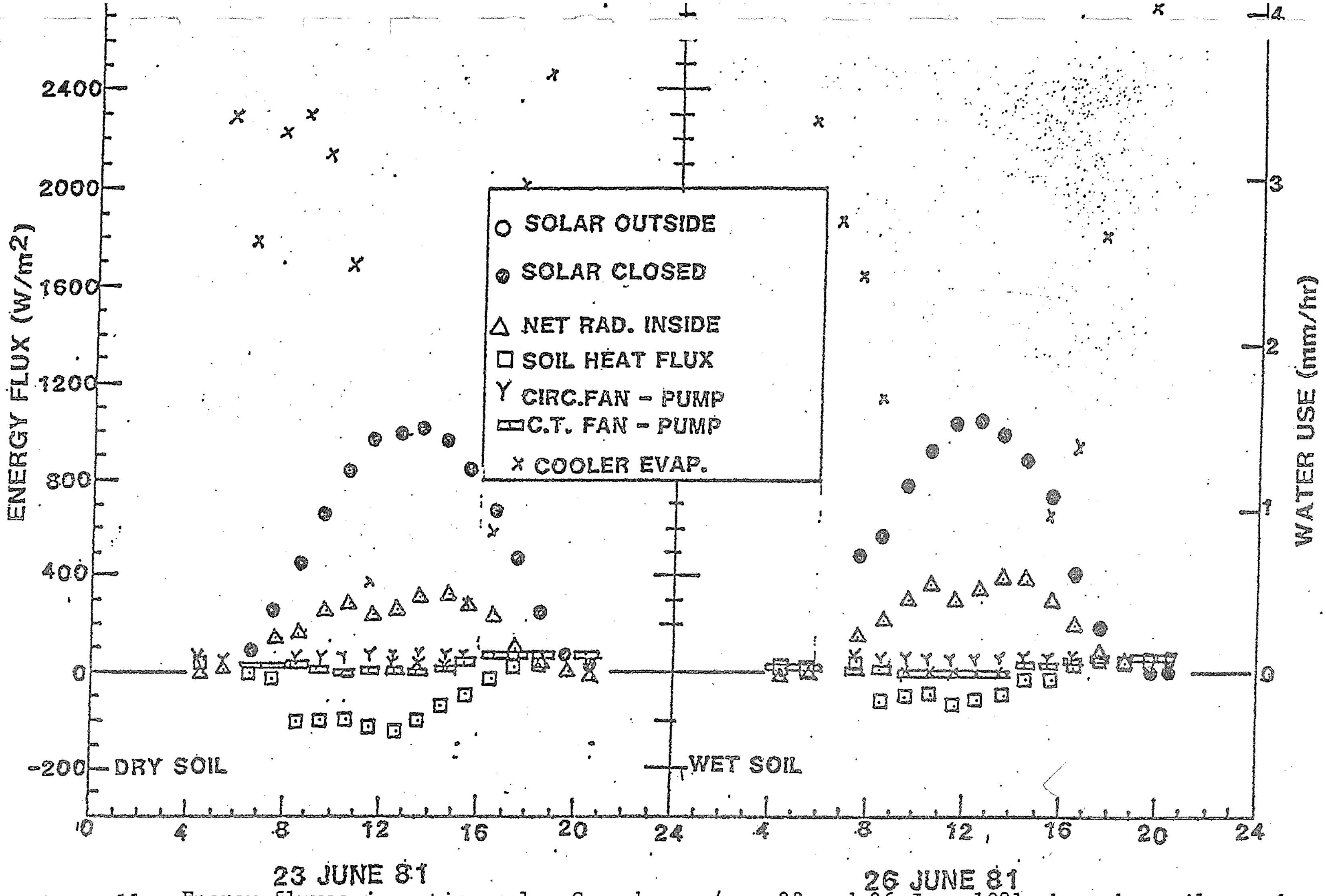


Figure 11. Energy fluxes in active solar Greenhouse 4 on 23 and 26 June 1981 when the soil was dry and wet, respectively. The fluxes include outside solar radiation (which is superimposed on the solar closed points), outside solar radiation received while the greenhouse was closed (and could have been enriched with CO_2), net radiation inside the greenhouse, soil heat flux (note the doubling of the scale for negative fluxes), electrical energy consumed by the cooling tower fan and pump, and the energy equivalent of the water evaporated by the cooling tower.

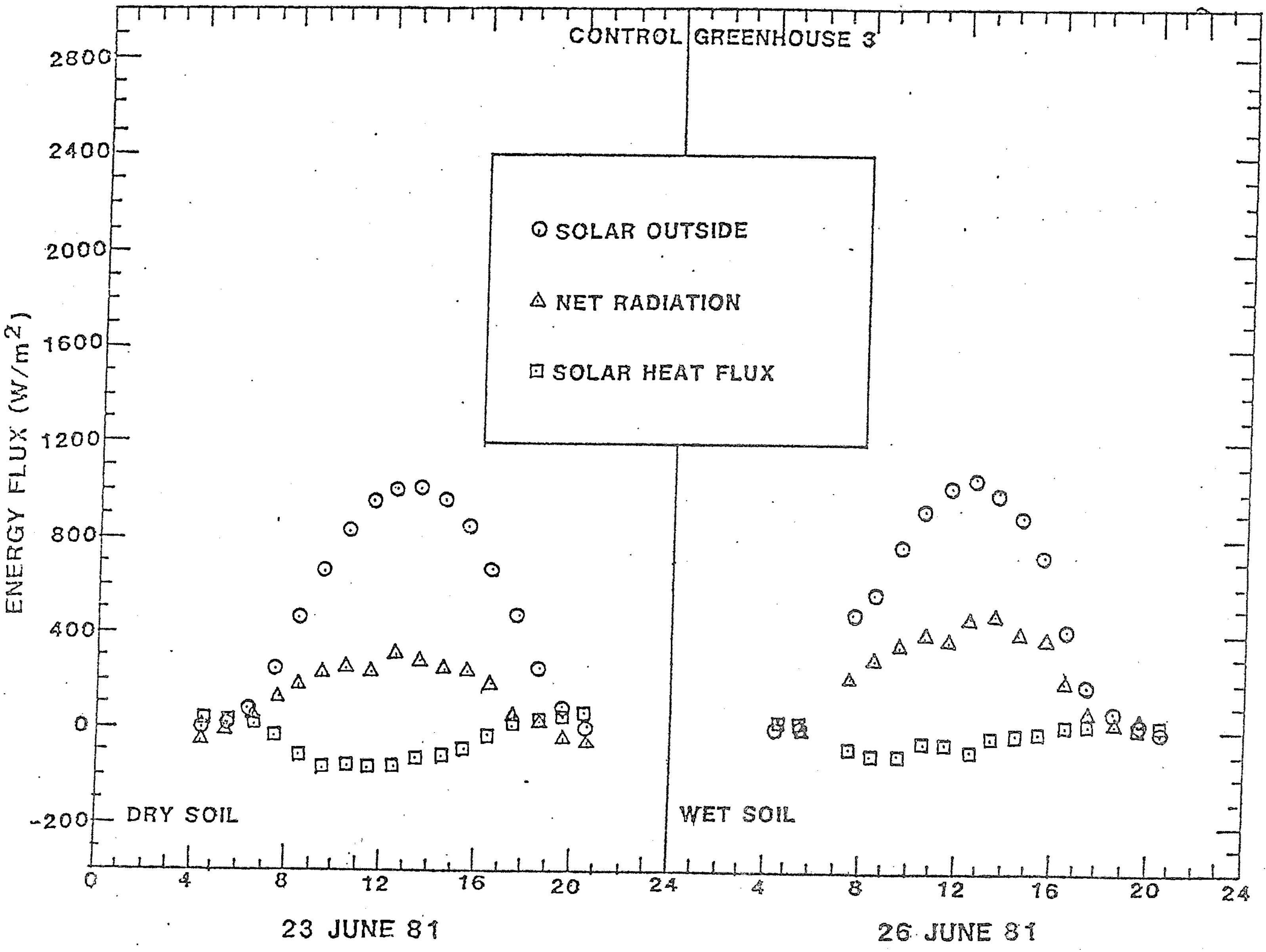


Figure [illegible]2. Fluxes of solar radiation outside, net radiation inside, and soil heat flux in Control Greenhouse 3 on 23 and 26 June 1981, when the soil was

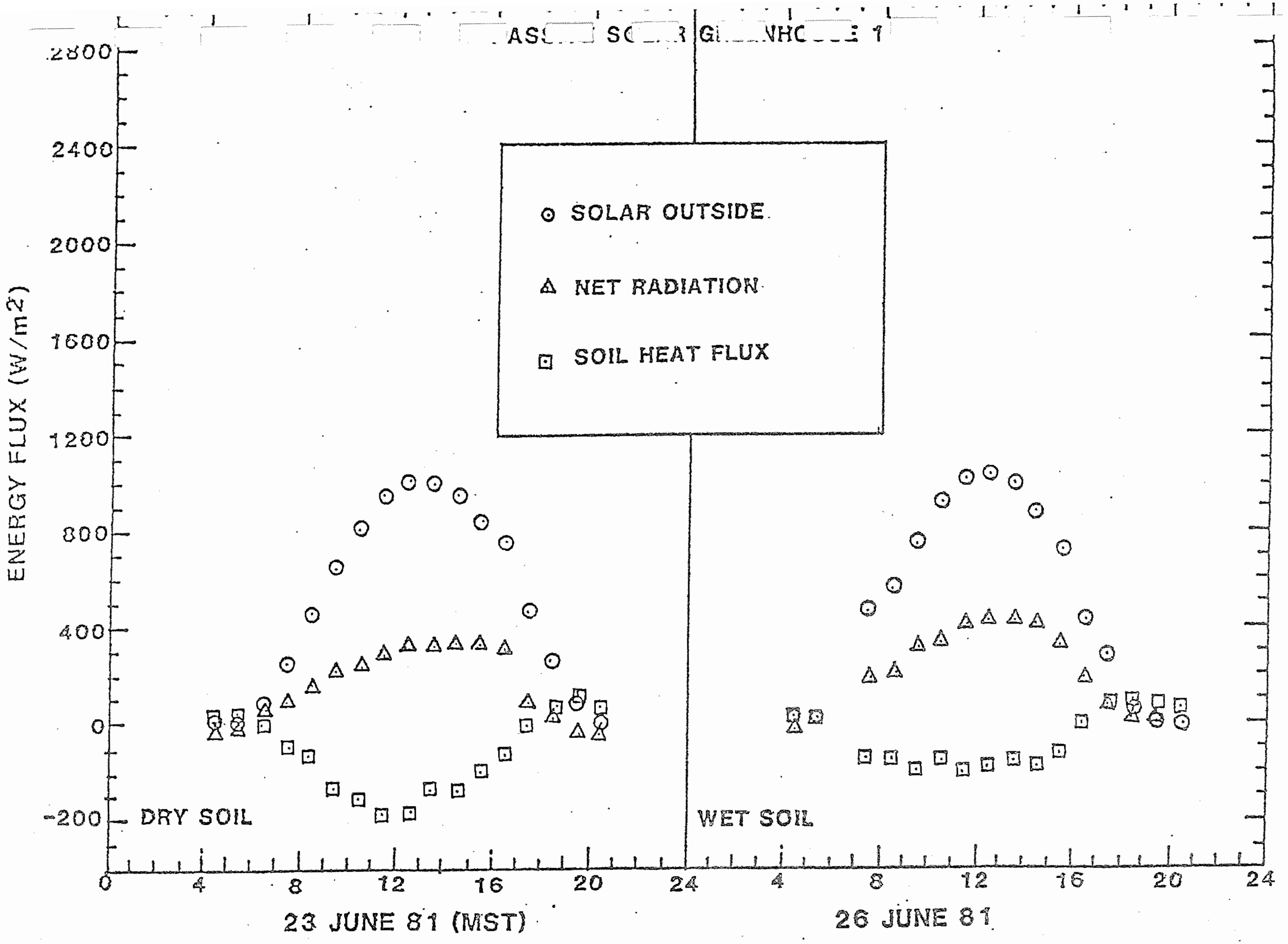
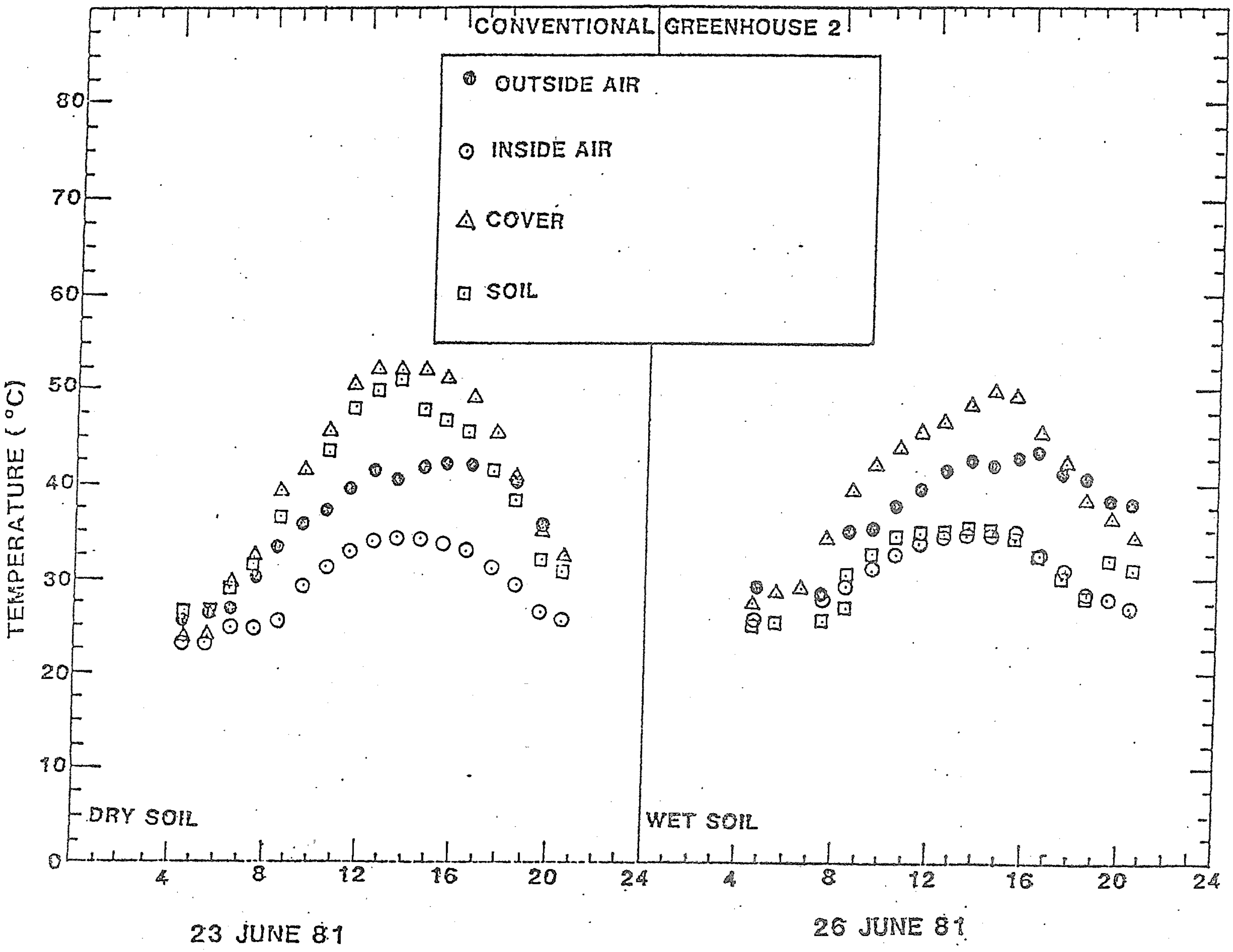


Figure 13. Fluxes of solar radiation outside, net radiation inside, and soil heat flux in passive Greenhouse 1 on 23 and 26 June 1981, when the soil was dry and wet, respectively. (Note the change in scale for negative values).



F e 1 Te atu f t out ai ins air ve nd . su ce (
conventional Greenhouse 2 on 23 and 26 June 1981, when the soil was dry

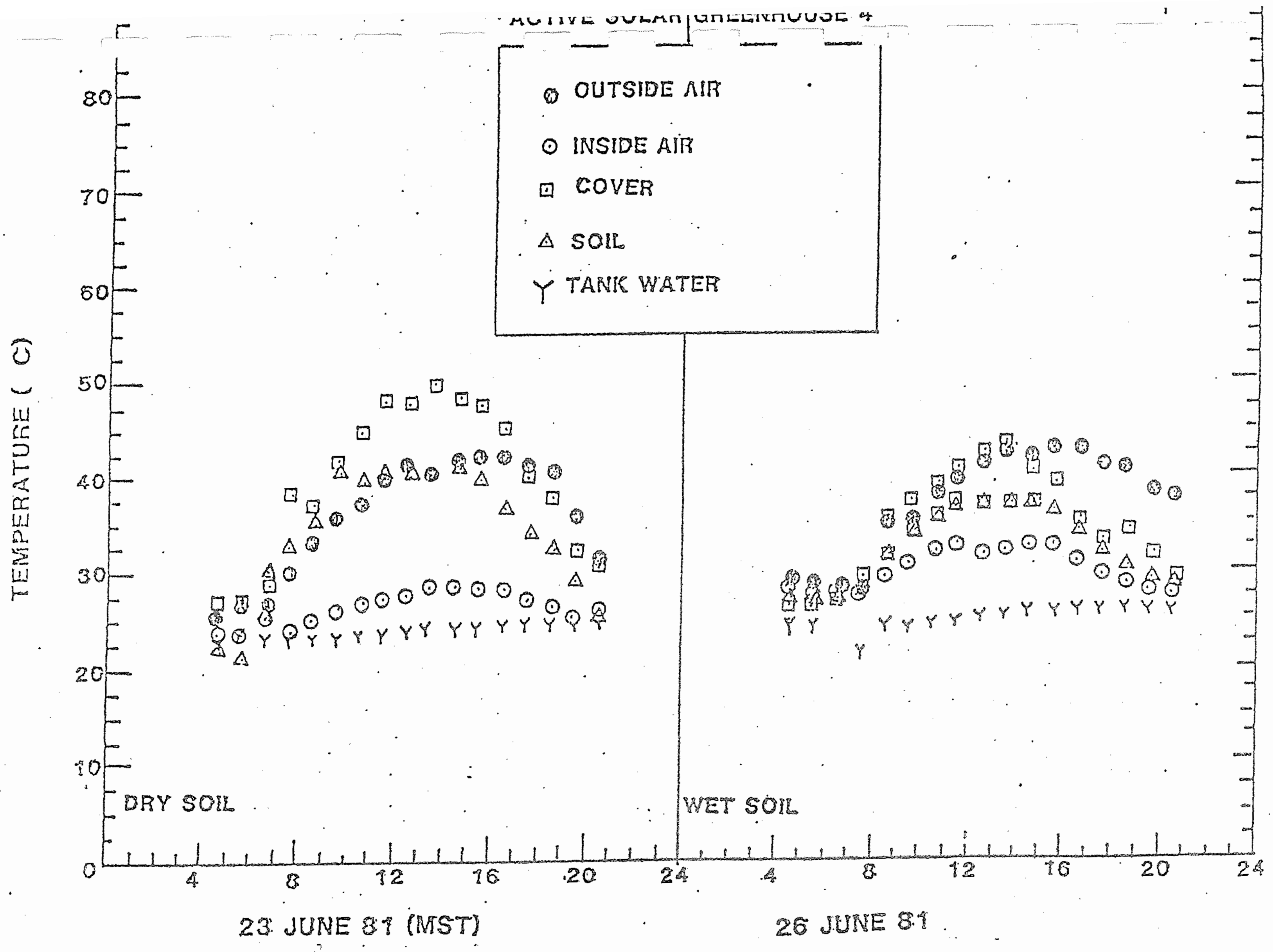


Figure 15. Temperature of the outside air, inside air, cover, soil surface, and storage tank water of active solar Greenhouse 4 on 23 and 26 June 1981, when the soil was dry and wet, respectively.

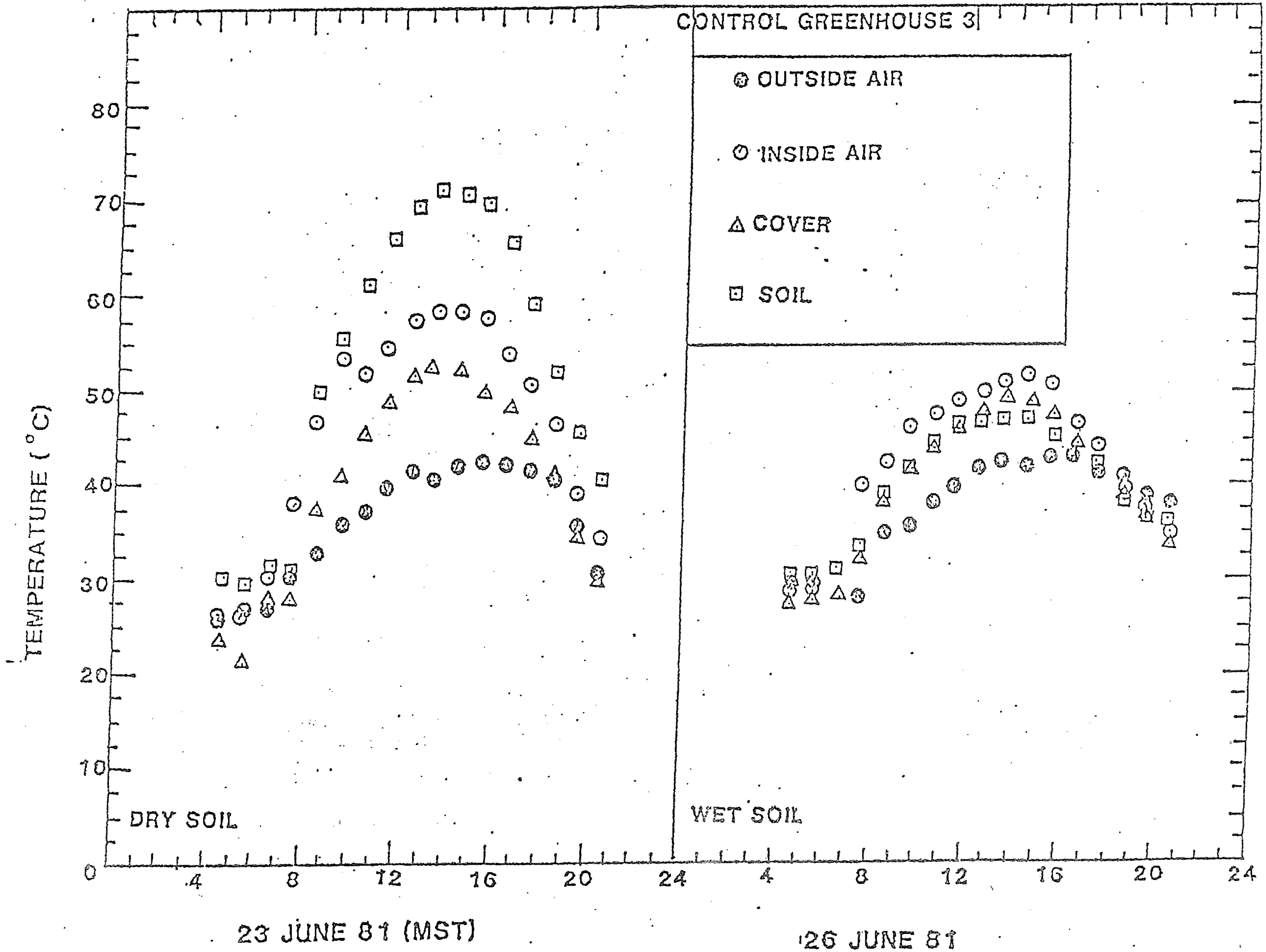


Figure 1[illegible]. Temperature of the outside air, inside air, cover, and [illegible] surface [illegible]
control Greenhouse 3 on 23 and 26 June 1981, when the soil was dry and [illegible]

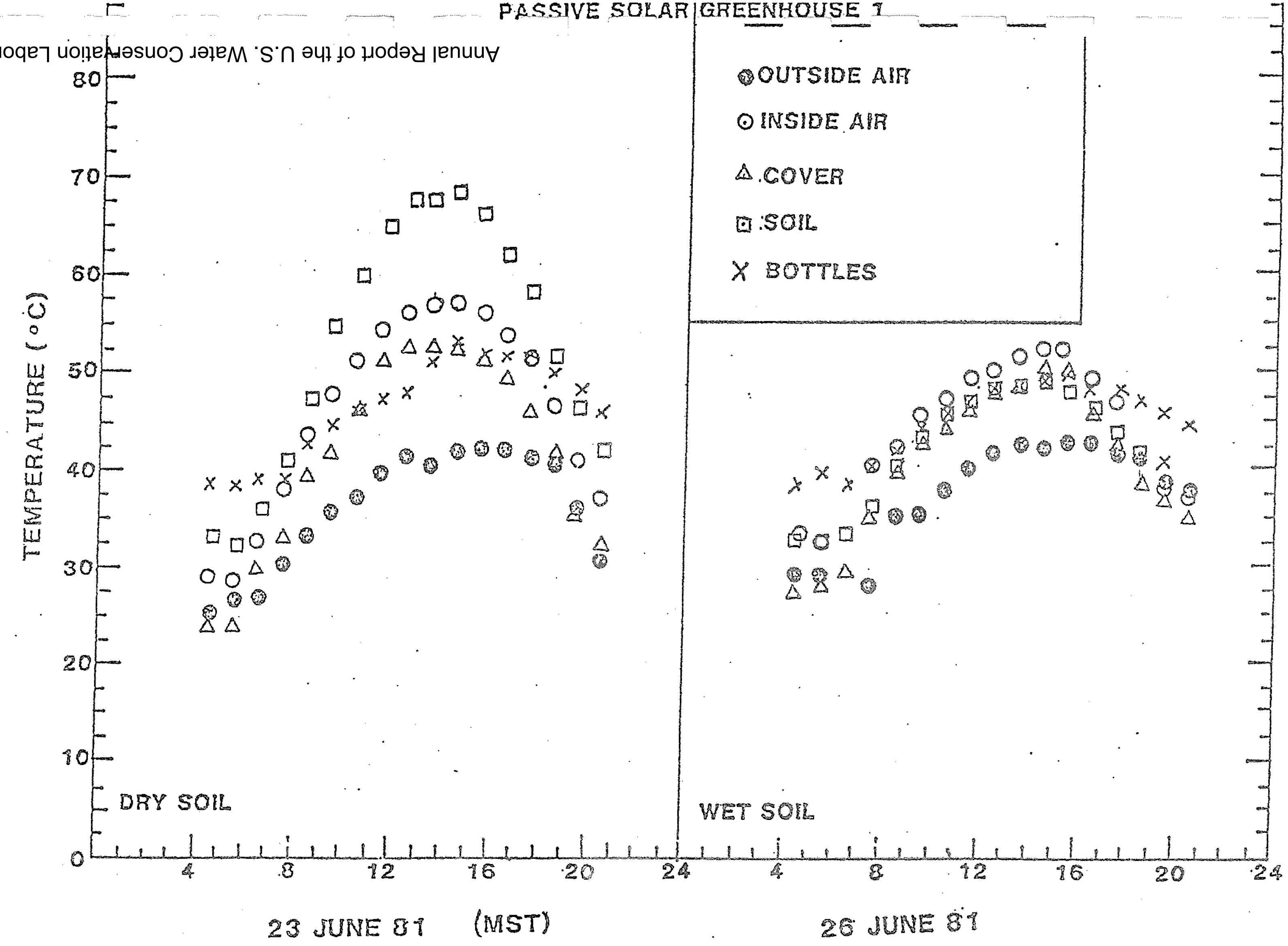


Figure 17. Temperature of the outside air, inside air, cover, soil surface, and water bottles of passive solar Greenhouse 1 on 23 and 26 June 1981, when the soil was dry and wet, respectively.

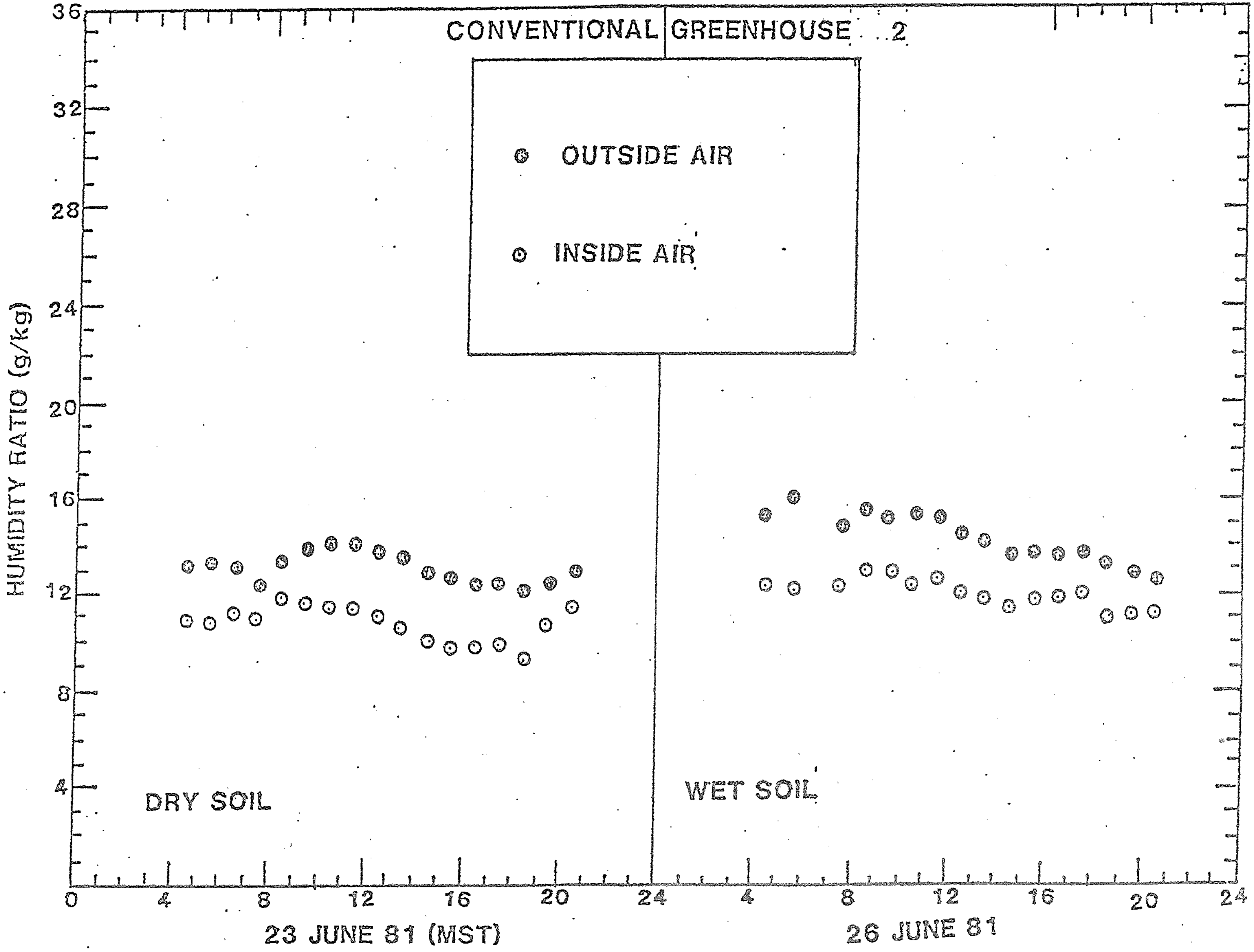


Figure 18. Humidity ratios of the air outside and inside conventional Greenhouse 2 on 23 and 26 June 1981, when the soil was dry and wet, respectively.

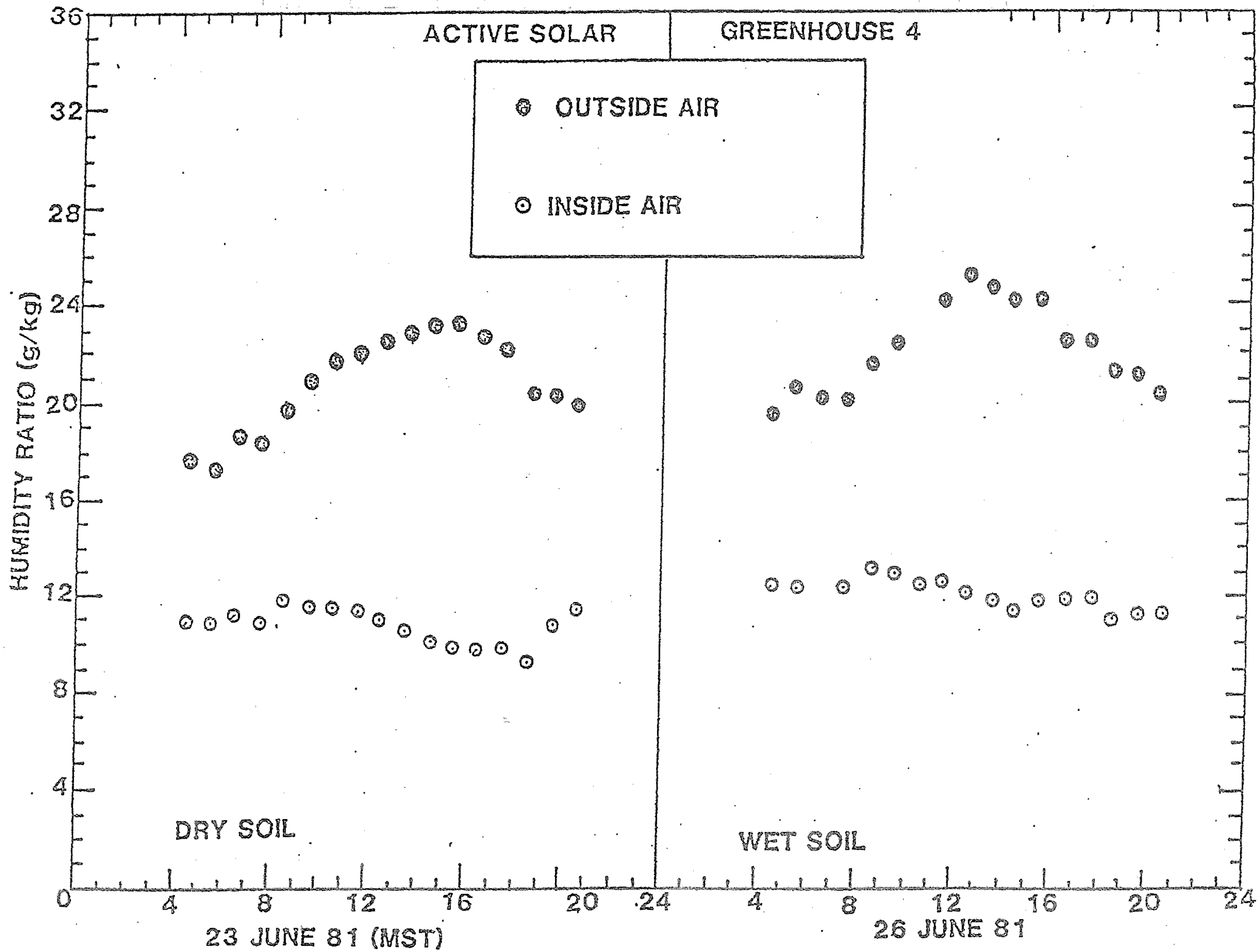


Figure 19. Humidity ratios of the air outside and inside solar Greenhouse 4 on 23 and 26 June 1981, when the soil was dry and wet, respectively.

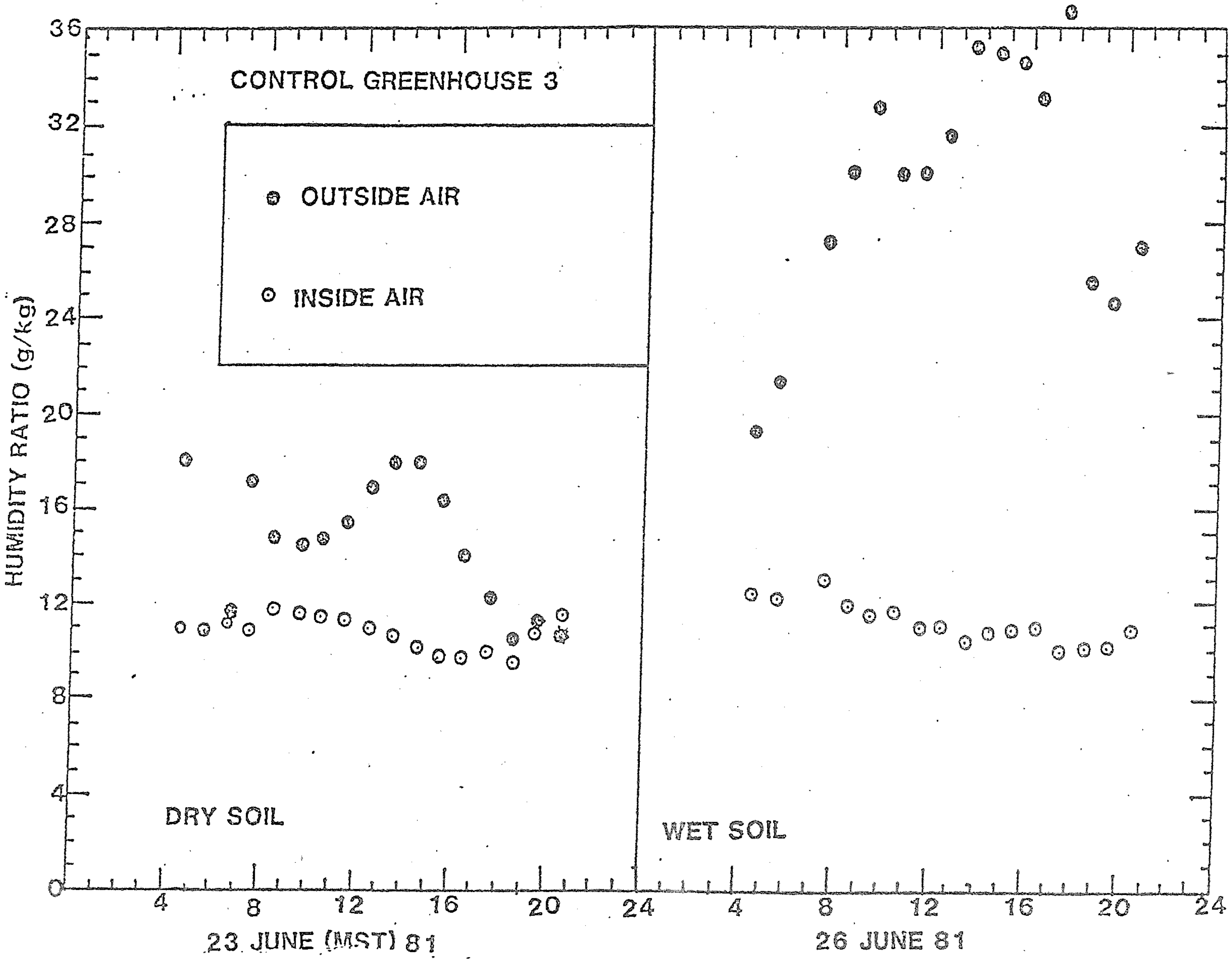


Figure 20. Humidity ratios of the air outside and inside control Greenhouse 3 on 23 and 26 June 1981 when soil was dry and wet, respectively.

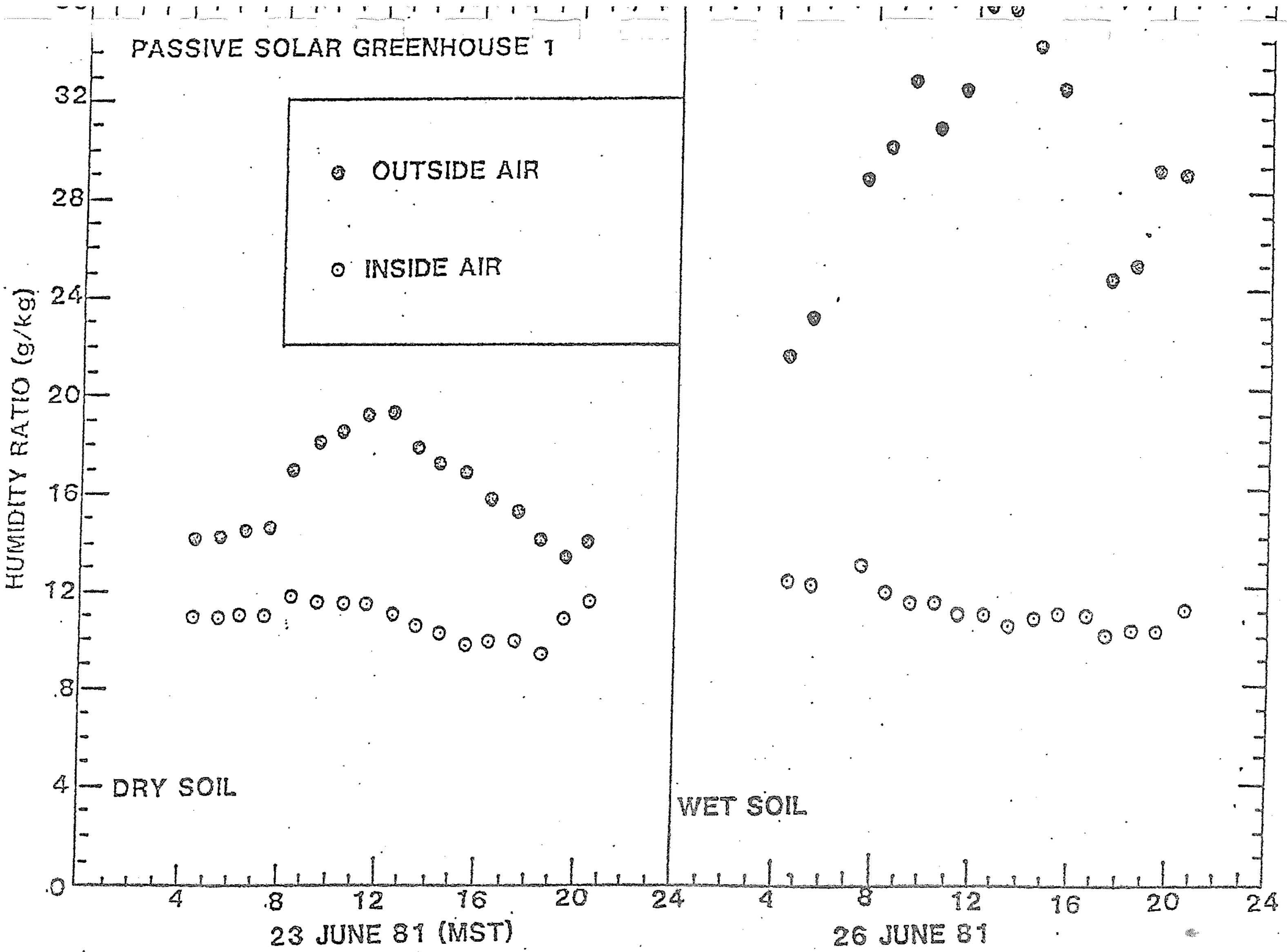


Figure 21. Humidity ratios of the air outside and inside passive solar Greenhouse 1 on 23 and 26 June 1981, when the soil was dry and wet, respectively.

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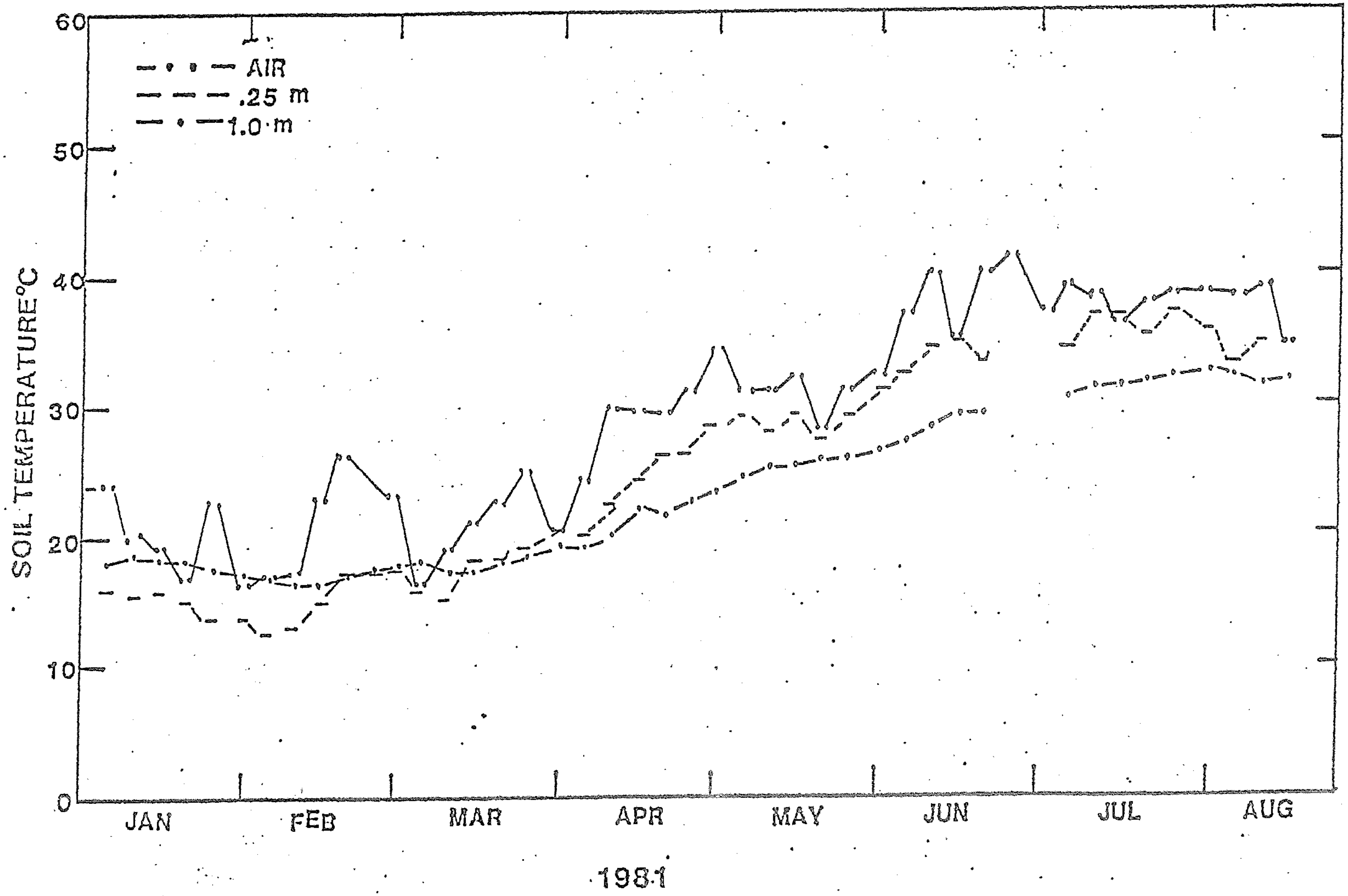


Figure 22. Soil temperature at midnight and average daily air temperature for bare ...dal loam in Pho...x, ...ona for 19... Ki... Mitchell, & G. Brooks, U. S. Water Conservation Laboratory 1981 Annual

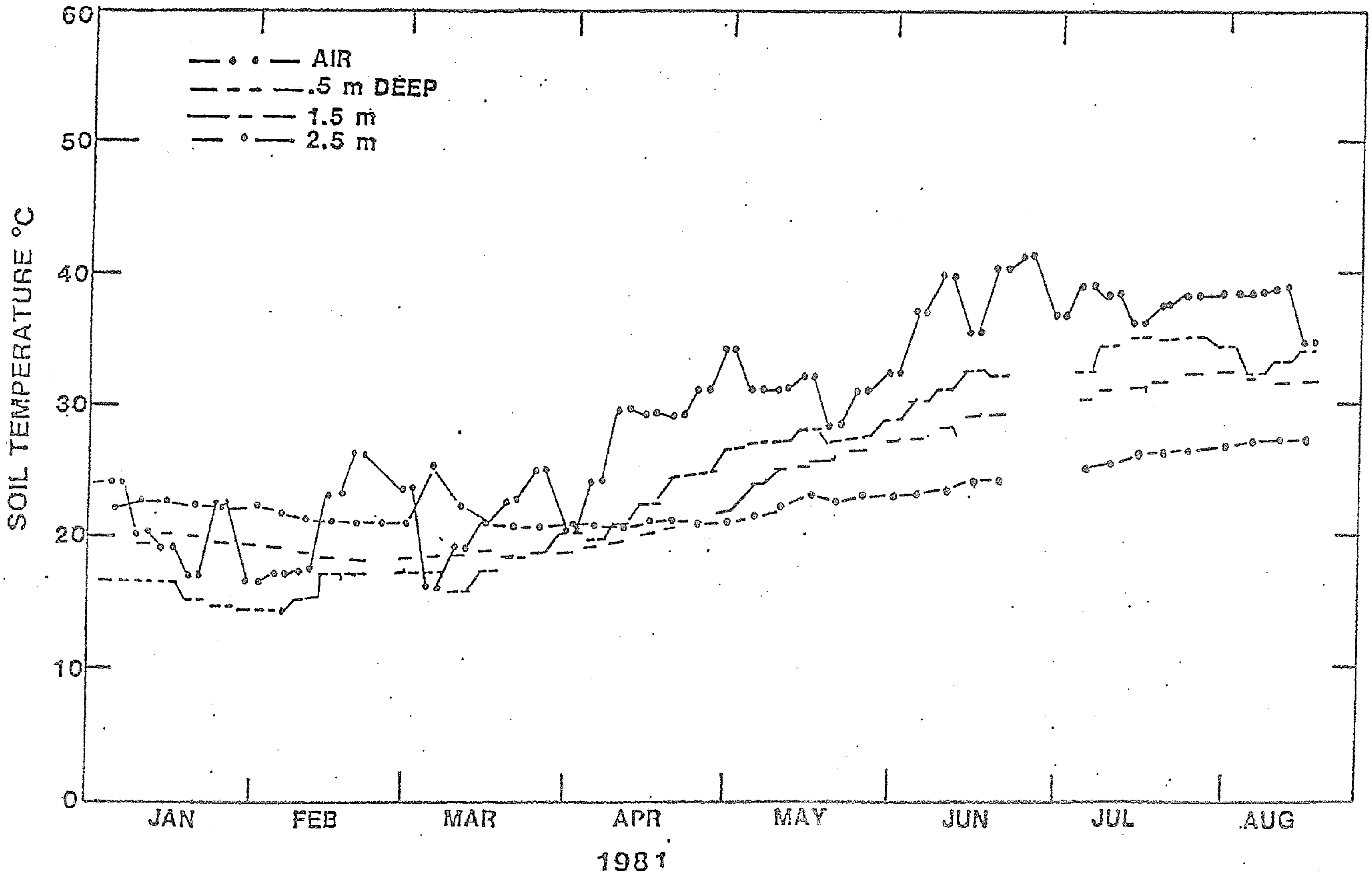


Figure 23. Soil temperatures at midnight and average daily air temperature for bare Avondale loam in Phoenix, Arizona for 1981. (From B. A. Kimball, S. T. Mitchell, & G. Brooks, U. S. Water Conservation Laboratory 1981 Annual Report.)

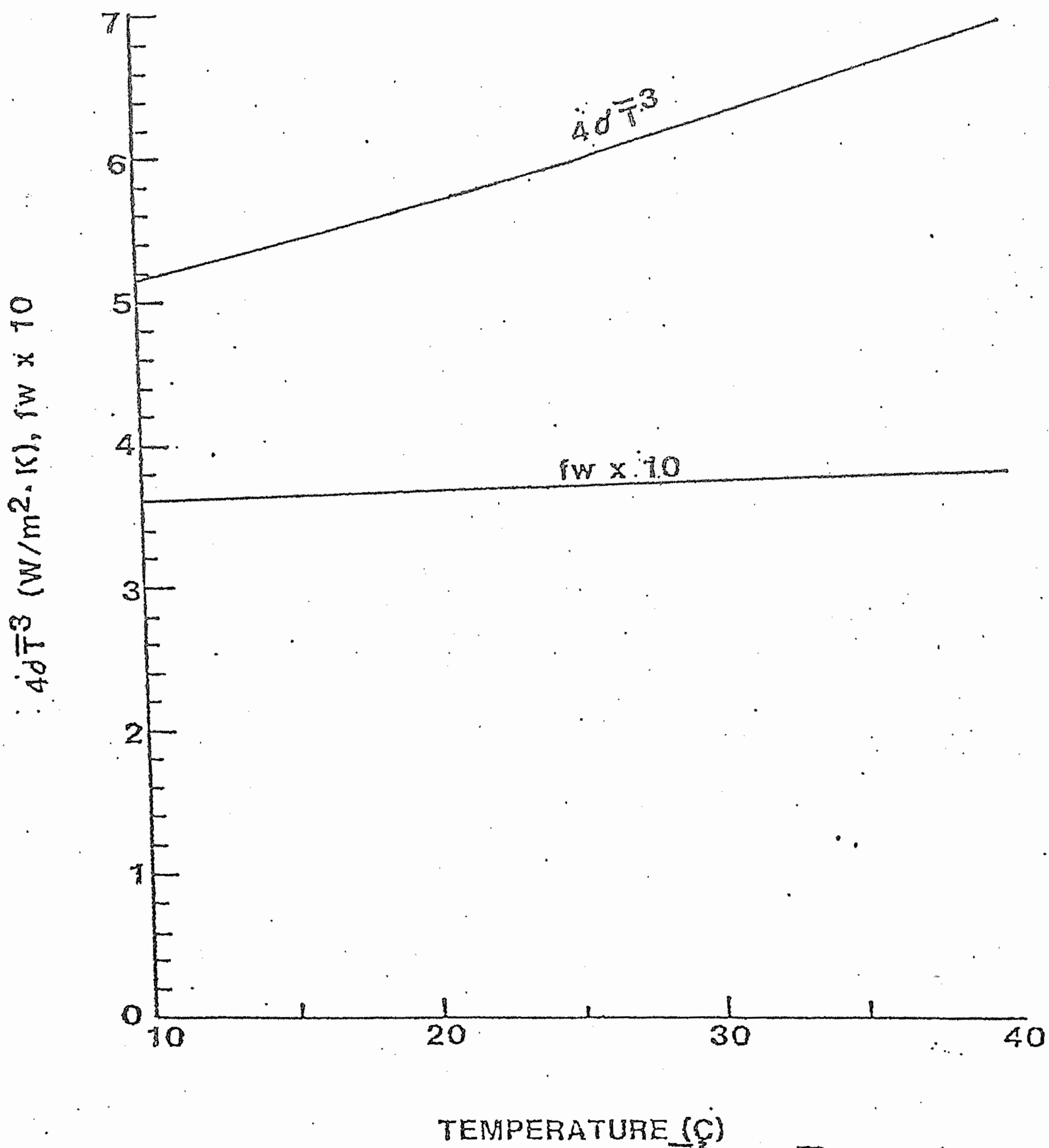


Figure 24. Plot of the Quantity $4\sigma\overline{\overline{T}}^3$ where $\overline{T}$ is in °K against temperature. Also the fraction of black body radiation emitted in the 8–14μm band, f_ω, against temprature. (Harrison 1960, Table 2).

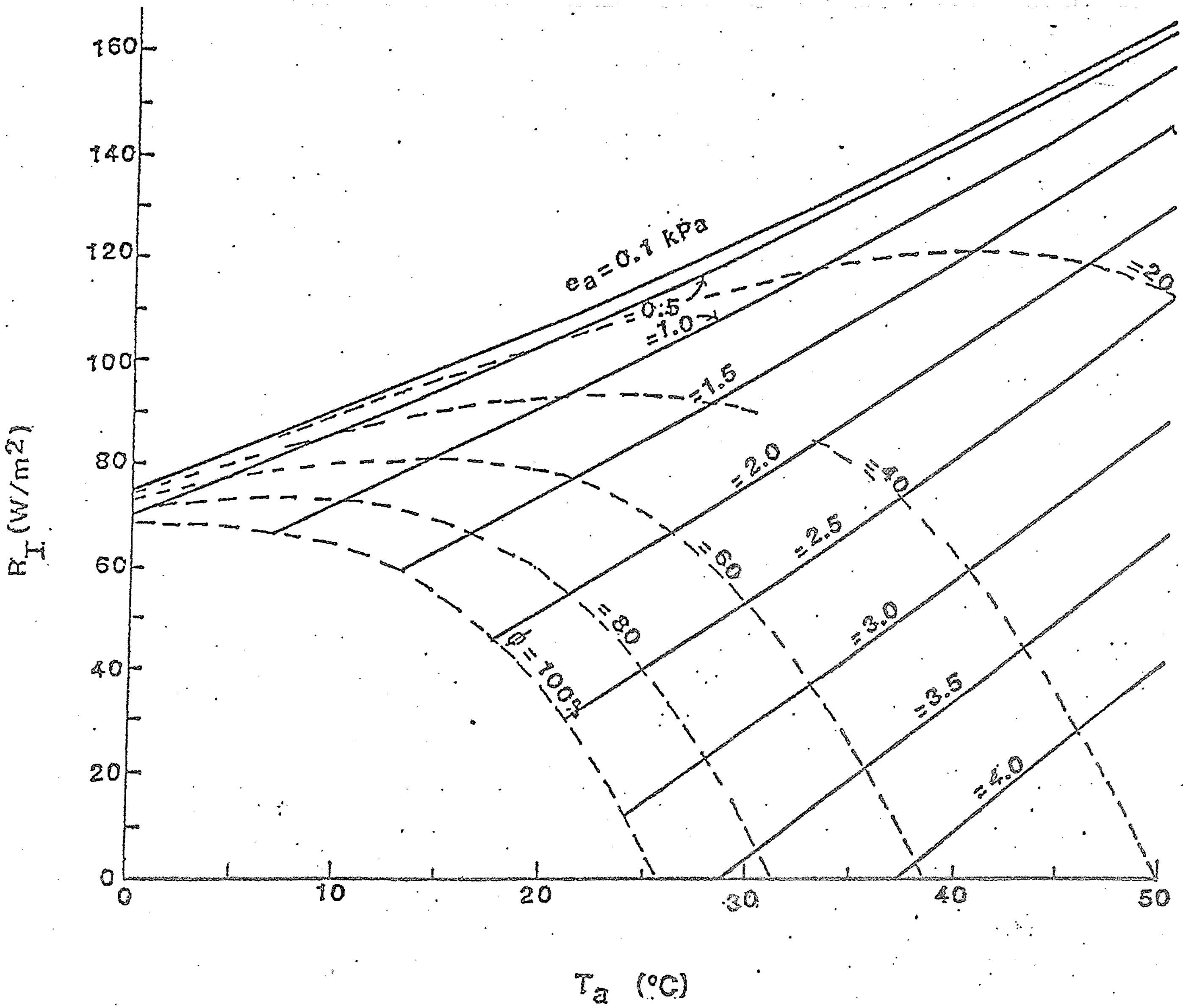


Figure 25. Power, R_I, at which atmosphere can receive radiation from an ideal radiator at air temperature, T_a, for various vapor pressures, e_a, and relative humidities, ∅.

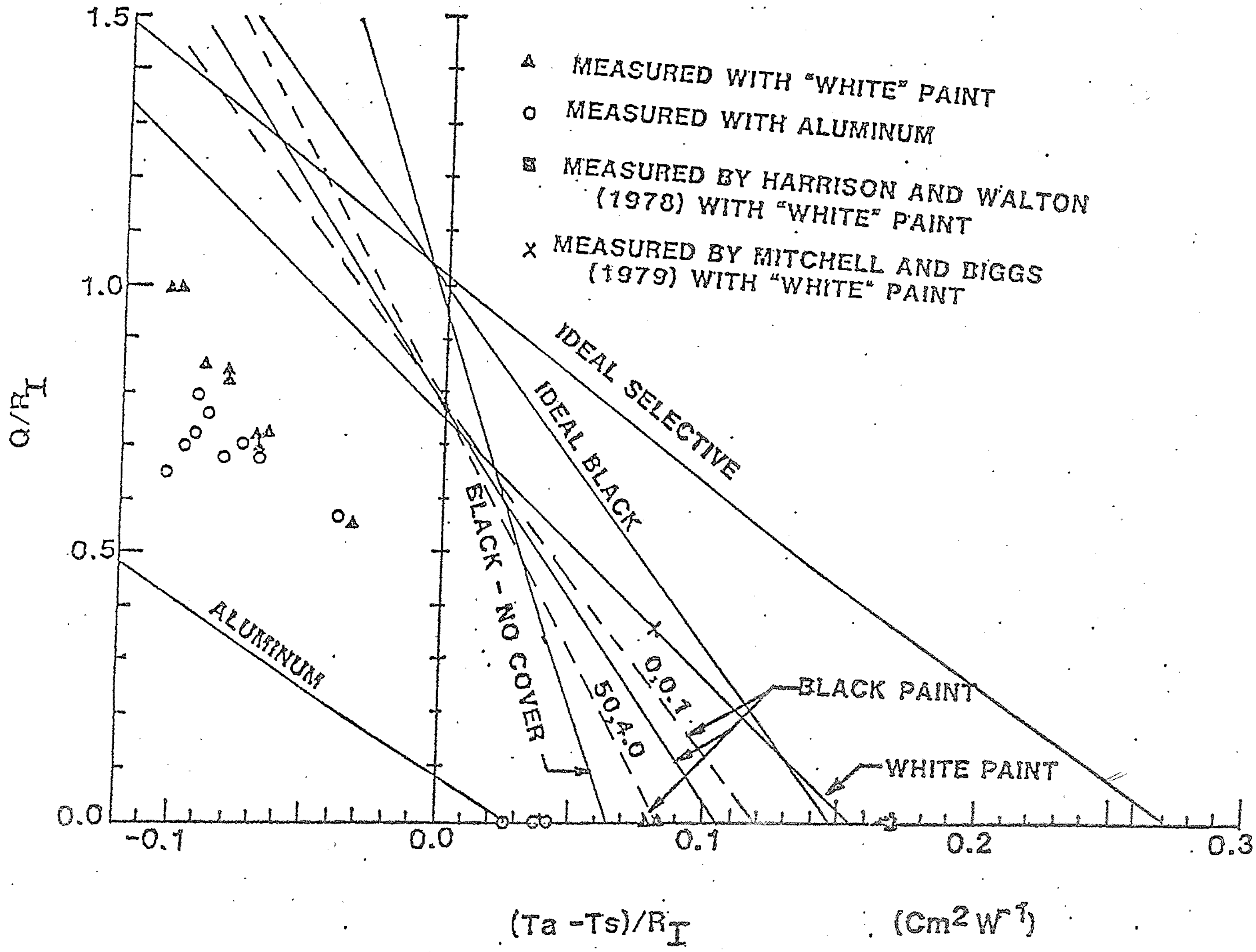


Figure 26. Measured values of the external energy, Q, supplied to a night sky radiator versus the temperature depression below air temperature (T_a – T_s), both normalized with respect to the ideal radiating power, R_I, and the

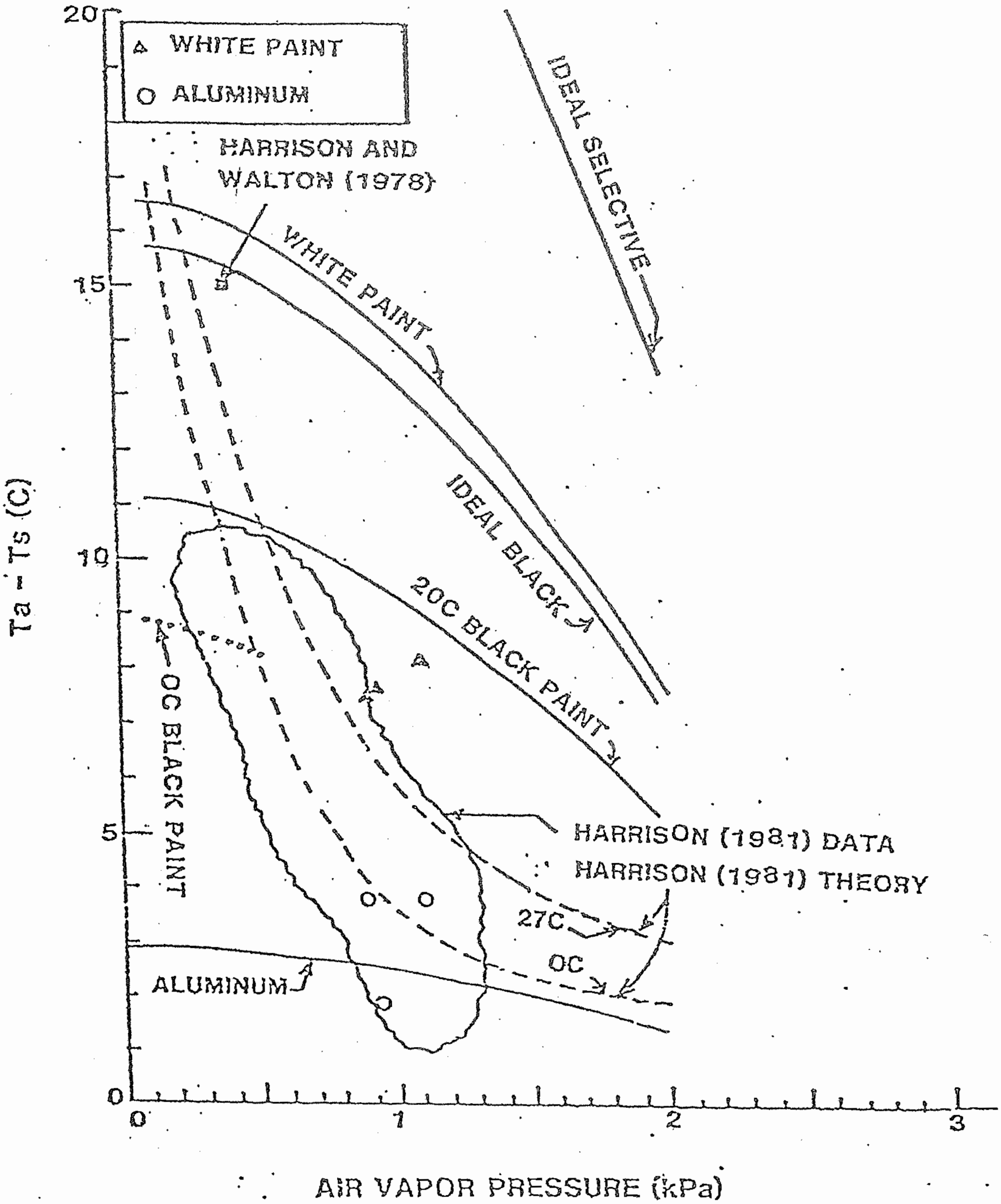


Figure 27. Depression of night sky radiator surface temperature below air temperature versus air vapor pressure when no external energy is supplied to the radiators (Q=0). The solid theoretical curves are for an air temperature of 20C.

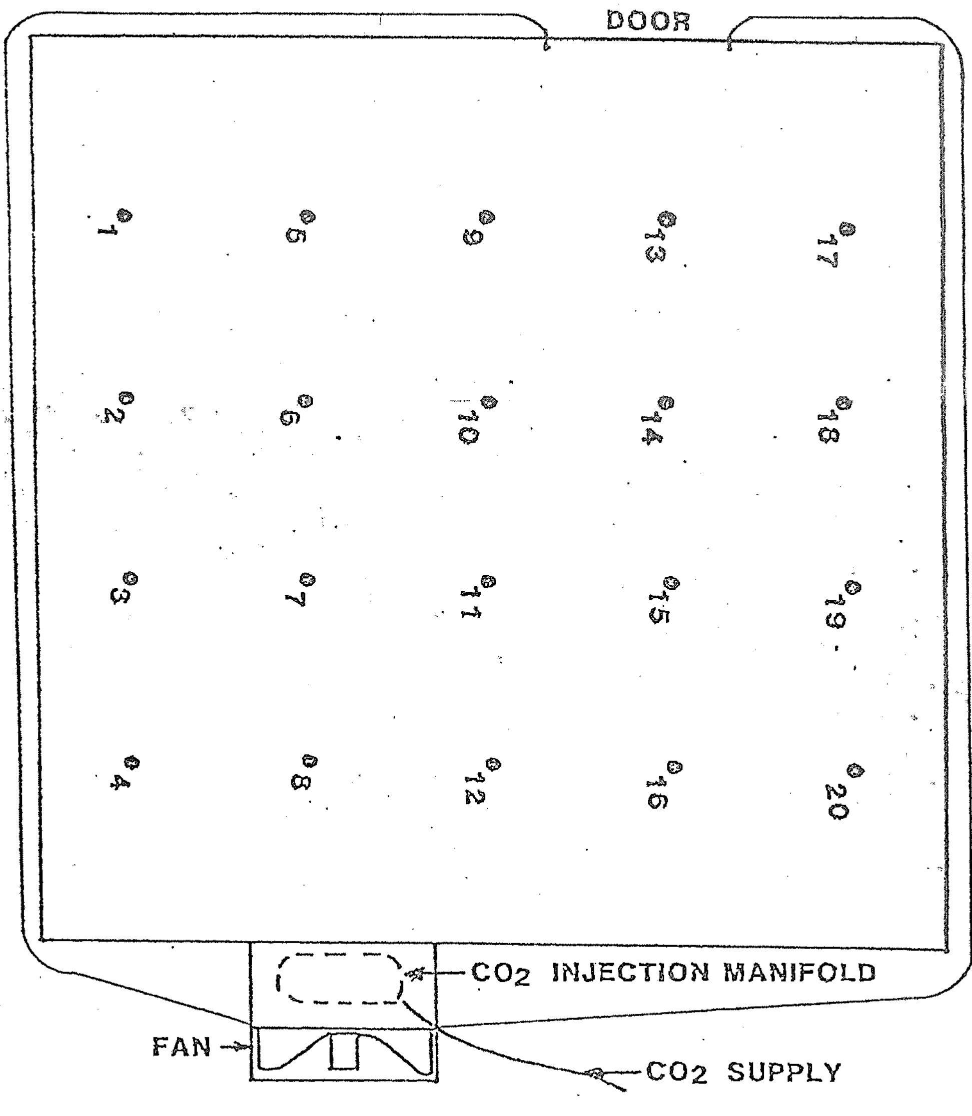


Figure 28. View from top of CO_2 enrichment chamber showing position of CO_2 sampling sites.

TITLE: MICROBIOLOGY OF SOIL AND WATER SYSTEMS FOR RENOVATION AND CONSERVATION OF WATER

NRP: 20790 CRIS WORK UNIT 5510-20790-002

INTRODUCTION:

During 1981, the biological studies on nitrification-denitrification reactions in soils intermittently flooded with primary or secondary sewage effluent were continued. Specifically, effects of chlorinated effluent on nitrogen transformations were evaluated, the causes of nitrification inhibition in primary sewage effluent chemically treated for odor control were determined, and the validity of nitrous oxide evolution during nitrification in soils intermittently flooded with secondary sewage effluent was investigated.

PROCEDURES:

The effects of chlorination of secondary sewage effluent on nitrogen transformation in soil basins at the 23rd Avenue project were determined. The project consisted of four large recharge soil basins (500 x 100 m) of about 10 acres that were intermittently flooded with effluent and dried, respectively, for 14 days each. The water depth in the basins during flooding was about 20 cm. Soil samples were periodically collected only during the dry periods. Subsamples were extracted and analyzed, as soon as possible, for inorganic nitrogen components with an Automatic Technicon Analyzer.

Laboratory soil columns were used to determine the influence of ferric-chloride treatments that were used for H_2S odor control, on nitrification in soil flooded with primary sewage effluent. Soil samples of 500 g from Basin #3 at the 23rd Avenue project were packed into duplicate soil columns to a depth of 5 cm. The soil column was flooded with a hydraulic head of 50 cm for 24 to 36 hours or until 20ℓ of the selected water source had infiltrated through the soil. The 20ℓ was equivalent to the volume of water applied to a soil basin during flood periods of seven days. After the soil column had drained by gravity, the soil was removed, placed in a beaker (500 mℓ), covered with aluminum foil and incubated for seven days under oxidizing conditions at room temperature. Subsamples of soil were removed at selected times, extracted immediately and analyzed for ammonium-N, nitrite-N, and nitrate-N. Soil water contents were also routinely determined throughout the incubation period. The degree of inhibition of nitrification in wastewater soils, as influenced by time of exposure and concentrations of H_2S, was determined. Soil columns, as described above, were amended with ammonium-N and treated with atmospheres containing 1 to 20 percent H_2S for 30 minutes to . days. After H_2S treatment, the soils were incubated for 1 to 8 days and periodically analyzed for inorganic nitrogen content.

The evolution of N_2O from nitrification and/or denitrification processes in soil basins intermittently flooded with secondary sewage effluent was determined. After flooding, surface soil samples (0-5 cm) were collected and amended with various concentrations of either NH_4-N, NO_2-N, or NO_3-N. Duplicate subsamples (25 g DW) of each treatment were placed in serum screw cap flasks (250 mℓ) and aerobically incubated at 28°C for 1 to 10 days. An identical series of treated flasks were injected with acetylene (0.1 Atm) to selectively inhibit nitrification. Gas samples (0.5 ml) were collected at various times during incubation and N_2O was analyzed gas chromatographically with a hot wire detector. After collecting gas samples aerobic incubations were maintained by briefly opening and flushing each flask with laboratory air.

RESULTS AND DISCUSSION:

Nitrification-denitrification reactions were similar in soil basins intermittently flooded with chlorinated and non-chlorinated secondary sewage effluent (Table 1). The results indicated that chlorinated effluents could be applied to land treatment systems without adversely affecting biological nitrogen removal processes.

The inhibition of nitrification in soil basins flooded with primary sewage effluent (Table 2) was not caused directly by the iron chloride solution (Table 3), that was added for odor control of hydrogen sulfide. But rather, the inhibition was probably caused by a combination of effects, including low temperatures, high soil moisture and high amounts of soluble and suspended sulfides. The inhibition of nitrification by H_2S during and after treatment increased with increasing concentrations of H_2S and treatment time. After 7 days treatment with 10 and 20 percent H_2S, nitrification was strongly inhibited (Table 4). Treatment times of 30 minutes reduced the rate of nitrification for only 3 to 4 days and nitrification rates were similar to control soils after 8 days (Table 5). The results obtained have indicated that the inhibition of nitrification by H_2S, when produced and evolved from wastewater land treatment systems, may reduce nitrogen removal by denitrification.

Nitrous oxide (N_2O) was only evolved in detectable amounts from soil incubated aerobically without acetylene and amended with NH_4-N and NO_2-N (Table 6). When acetylene was present N_2O was evolved only from soil amended with NO_2-N (Table 7). Under aerobic conditions N_2O was not evolved from any soil samples amended with NO_3-N. These results have indicated that the source of N_2O evolution during drying of soil wastewater basins resulted from denitrification of NO_2-N and not from nitrification of NH_4-N.

SUMMARY AND CONCLUSIONS:

During 1981, the biological studies on nitrification-denitrification reactions in soils intermittently flooded with primary or secondary sewage effluent were continued. Specifically, effects of chlorinated effluent on nitrogen transformations were evaluated, the causes of nitrification inhibition in primary sewage effluent treated with an iron chloride solution for H_2S odor control were determined, and the validity of nitrous oxide evolution during nitrification in soils intermittently flooded with secondary sewage effluent was investigated.

Nitrification-denitrification reactions were similar in soil basins intermittently flooded with chlorinated and non-chlorinated wastewater, indicating that biological nitrogen removal processes in land treatment systems were not adversely affected by applications of chlorinated effluents. The inhibition of nitrification in soil basins flooded with primary sewage effluent was not caused directly by adding an iron chloride solution for odor control of hydrogen sulfide (H_2S).

The inhibition of nitrification in soil during and after treatment with H_2S increased with increasing atmospheric conditions of H_2S and treatment time. H_2S was apparently a bacteriostatic, rather than a bacteriocidal, agent against nitrifying bacteria. Treatment times of 30 minutes reduced the rate of nitrification for only 3 to 4 days. The results have indicated that the inhibition of nitrification by H_2S, when produced and evolved from wastewater land treatment systems, may reduce nitrogen removal by denitrification.

The evolution of N_2O from nitrification and/or denitrification processes in soil basins intermittently flooded with secondary sewage effluent was determined. N_2O was evolved from aerobic soil amended with ammonium-N and nitrite-N. When nitrification was inhibited with acetylene, N_2O was evolved only from soil amended with nitrite-N. Thus, the source of N_2O evolution during drying of soil wastewater basins resulted from denitrification of nitrite-N and not from the nitrification of ammonium-N.

This CRIS Work Unit will be terminated during CY 1982. Papers will be written for publication in appropriate journals, covering work on nitrification-denitrification reactions in soils intermittently flooded with secondary sewage effluent, effects of effluent chlorination on nitrogen transformations in basin soils, effect of hydrogen sulfide on nitrification in soil, source of nitrous oxide evolution during nitrification-denitrification reactions in soil, and other basic aspects of nitrogen transformations in soil.

REFERENCES AND PRESENTATIONS:

BOUWER, H, RICE, R. C., LANCE, J. C., and GILBERT, R. G. Rapid infiltration systems for renovating sewage. In Proc. of Third Northwest On-Site Wastewater Disposal Short Course. March 4-5, 1980. Univ. of Washington, Seattle, WA. Robert W. Seabloom (ed.). pp. 128-160. 1981

GILBERT, R. G. Source of Nitrous Oxide Evolution in Soils Intermittently Flooded with Secondary Sewage Effluent. Western Soil Science Society Annual Meetings, Eugene, Oregon, June 1981.

Gilbert, R. G. Effect of hydrogen sulfide on nitrification in soil. Soil Science Society of America Annual Meetings, Atlanta, GA, November 1981.

PERSONNEL: R. G. Gilbert and J. B. Miller

Table 1. Nitrogen transformations in soil basins intermittently flooded with non-chlorinated and chlorinated secondary sewage effluent at the 23rd Avenue project.

Days Dry	Soil Nitrogen Ammonium-N (μg n/g)	Soil Nitrogen Nitrified-N (μg n/g)	Water Content (%)
Non-Chlorinated Effluent 1/			
1	170	6	29.6
2	81	47	21.4
3	45	102	18.0
7	28	158	8.6
10	20	188	6.8
Chlorinated Effluent 2/			
1	117	12	24.9
2	53	65	19.0
3	26	90	13.1
7	13	100	9.4
10	13	135	6.9

1/ Data are average from 5 day periods during July - September, 1980.
2/ Data are average from 3 dry periods during March, April, and June, 1981.

Table 2. Nitrification in soil basin intermittently flooded with primary sewage effluent.

Soil Basin Schedule	Nitrogen Content (μg/g) Ammonium-N	Nitrogen Content (μg/g) Nitrified-N
1 Week Flood	216	0
1 Week Dry	185	10

Table 3. Nitrification in soil from columns flooded with secondary sewage effluent amended with solutions of iron chloride (113 mℓ/20 ℓ).

Incubation time (days)	Nitrogen Content (μg/g) Ammonium-N		Nitrified-N	
	$-FeCl_2$	$+FeCl_2$	$-FeCl_2$	$+FeCl_2$
0	82	76	0	0
8	7	14	90	87

Table 4. Nitrification in soil treated with different atmospheric concentrations of hydrogen sulfide.

H_2S treatment (%)	Incubation Time (Days)	Nitrogen Content (μg/g) Ammonium-N	Nitrified-N
0	0	243	33
0	7	36	176
1	7	35	118
5	7	84	> 1
10	7	224	> 1
20	7	271	2

Table 5. Nitrification in soil treated with 20% H_2S atmosphere for 30 minutes and incubated for 8 days.

Incubation time (Days)	Nitrogen content (μg/g) Ammonium-N		Nitrified-N	
	Control	H_2S	Control	H_2S
0 (T-0)	117	117	56	56
0 (T-30 min)	100	129	78	63
1	24	86	183	74
2	30	94	219	84
4	31	44	231	174
8	16	21	299	231

Table 6. N_2O evolution from well-aerated soils treated with different forms of nitrogen. Ammonium-N as $(NH_4)SO_4$; nitrite-N as KNO_2; nitrate-N as KNO_3.

Nitrogen Treatment		Accumulative N_2O evolution		
		2 days	4 days	8 days
(form)	(μg/g)		(μg/g)	
- Wastewater soil: Loamy sand from Salt River bed -				
None		0	0	0
Ammonium-N	100	0	1.1	2.1
Nitrite-N	100	0	1.1	2.1
Nitrate-N	100	0	0	0
Ammonium-N	400	12.0	22.7	29.1
Nitrite-N	400	12.7	24.4	44.2
Nitrate-N	400	0	0	0
- Agricultural soil: Avondale loam from Cotton Research Center -				
None		0	0	0
Ammonium-N	400	0	0	0
Nitrite-N	400	0	0	0
Nitrate-N	400	0	0	0

Table 7. Effect of acetylene on N_2O evolution from wasteater soil treated with different forms of nitrogen, various concentrations of nitrite-N and incubated under aerobic conditions. 1/

Soil nitrogen treatments		Accumulative N_2O evolution					
		2 days	4 days	8 days	2 days	4 days	8 days
		- acetylene			+ acetylene 2/		
(form)	(μg/g)		(μg/g)			(μg/g)	
None		0	0	0	0	0	0
Ammonium-N	400	12.0	22.7	29.1	0	0	0
Nitrate-N	400	0	0	0	0	0	0
Nitrite-N	400	12.7	24.4	44.2	9.3	25.4	102.9
Nitrite-N	200	5.4	16.1	26.5	5.9	43.3	165.8
Nitrite-N	100	2.7	10.7	14.7	4.3	19.3	94.2
Nitrite-N	75	2.7	7.0	10.7	2.7	9.1	28.9
Nitrite-N	50	2.7	5.4	7.0	2.7	5.4	9.1
Nitrite-N	25	1.1	2.1	3.2	1.1	1.1	1.1

1/ Soil samples of 30g were treated with ammonium-N as (NH_4); nitrate-N as KNO_3; and nitrite-N as KNO_2 and incubated at 28°C. The soil water content was about 60% of the water-holding capacity.

2/ The atmospheres of the 250 mℓ incubation flasks contained 0.1% (vol/vol) acetylene. Flask atmospheres were renewed after 2 and 4 days.

TITLE: WASTEWATER RENOVATION BY SPREADING TREATED SEWAGE FOR GROUNDWATER RECHARGE

NRP: 20790 CRIS WORK UNIT 5510-20790-003

INTRODUCTION:

The infiltration basins of the 23rd Avenue project were operated at a schedule of two weeks flooding--two weeks drying to study trace organics in the chlorinated treatment plant effluent and in the resulting renovated water pumped from the aquifer. These studies were a continuation of work done in the period September-November 1980, when the secondary effluent from the sewage treatment plant was not yet chlorinated. The chlorination facility at the treatment plant was put into operation at the end of November, dosing the effluent at a rate of 1.5 mg Cl/ℓ. In the period April-June 1981, weekly samples of sewage effluent and renovated water were again analyzed for trace organics. Comparing the results with those obtained in the sampling period of fall of 1980 thus indicates the effect of chlorination on the type and concentration of trace organics in the effluent and their fate in the infiltration-recharge system. This effect must be known because it determines the suitability of chlorinated effluent for groundwater recharge and the need for dual outfall systems if part of the effluent is to be used for rapid infiltration and the rest for normal discharge into surface water.

The trace organics analyses again were performed by the Environmental Engineering and Science Group, Civil Engineering Department, Stanford University, CA. The samples were also analyzed in-house for routine parameters such as the various forms of nitrogen, phosphorus, fecal coliforms, total organic carbon, and others. On 30 June 1981, the basins were dried to permit removal of weeds that had started to proliferate in the basins. Shore vegetation on the dikes of the infiltration basins was also removed and the bypass channel was cleaned. After the cleaning operations, the system was not put into use again because of various construction activities involving the effluent channel system. With the drying of the basins on 30 June 1980, the research activities of the U. S. Water Conservation Laboratory at the 23rd Avenue project officially came to a halt. In the future, the basins may be periodically flooded for maintenance or demonstration-type purposes. No further research is planned at this time. The results presented in this report thus refer to the first six months of 1981 only.

Most of the efforts of the Subsurface Water Management Group will be redirected toward evaluating the effects of irrigated agriculture on recharge and quality degradation of underlying groundwater. To obtain a better understanding of downward flow in the vadose zone and of the effect of the presence of boulders and rock strata in this zone on the transport of water and chemicals, a laboratory column 2.83 m high and 1.24 m in diameter was filled with coarse sand and layers of boulders. Water was applied to the top of the column at various rates and for various lengths of time. The resulting flow systems and transport of conservative tracers were determined and supplemented with measurements of water content and pressure head profiles in the column for proper analysis of the data.

I. 23RD AVENUE PROJECT

1. INFILTRATION RATES

The basins were inundated on a two-week drying-two-week flooding cycle. Inflow rates of secondary effluent into the basins were set to minimize the water depth in the basins. Often, the water did not quite reach the outlet ends of the basins and sometimes covered only about 2/3 or 3/4 of the basin area. The water depth in the basins averaged about 0.2 m. Small water depths were maintained to maximize the turnover rate of the water in the basins, thus minimizing the chance for development of suspended algae in the water and resulting clogging of the basin soil. The shallow water encouraged the growth of weeds in the basins, which in turn aggravated the mosquito problem. Main plant species were barnyard grass (Echinochloa Crusgalli), willow leaf (Polygonum lapathifolium), and salt cedar (Tamarix sp.). Periodic large water depths and occasional maintenance probably can eliminate most of the weed growth.

Infiltration rates were calculated from inflow measurements and area of basin covered. The infiltration rates started out relatively high (Figures 1, 2, 3, and 4) and often were more than 1 m/day. The rates generally declined to around 0.5 m/day or less after two weeks of flooding. Infiltration recoveries during drying were excellent, except in Basin 4 which had some low areas where water remained standing for most of the drying period. Also, the gate controlling the inflow of Basin 4 could not be completely closed. The resulting leakage produced permanent flooding of a few acres around the inlet end, which reduced the effective area for rapid infiltration. The average infiltration rate during flooding was 0.63 m/day for Basin 1, 0.82 m/day for Basin 2, 0.74 m/day for Basin 3, and 0.24 m/day for Basin 4 (Table 1). This produced hydraulic loading rates of 43.9, 57.3, 51.5, and 17.1 m, respectively, for the first half of the year, or an average of 42.4 m. Multiplying this figure by two gives an annual hydraulic loading rate of 84.8 m for the entire project. Without problems of low spots and a leaking inlet gate, Basin 4 probably could have had a similar infiltration rate as the other basins. Assuming an average infiltration rate for Basin 4 of 0.72 m/day instead of the actual rate of 0.24 m/day would increase the hydraulic loading rate of the entire project to 51 m for the first six months or to 102 m/year. At this rate, the 16-ha (40-acre) system would have a capacity of 16.3 million m^3/year, or 13,231 acrefeet/year or 11.8 million gallons/day.

2. GROUNDWATER LEVELS

Groundwater levels in the beginning of 1981 were at about 305.5 m above sea level, or about 8.5 m below the bottom of the basins. Ground-water levels were not measured in 1981. Based on groundwater level measurements in 1976, which also was a year of no spring runoff in the Salt River, groundwater levels in 1981 probably remained fairly stable for January and February, and then declined at a rate of about 1 m per month as irrigation wells north of the project began to pump. Thus, the depth of the water able at the end of June probably was about 12 m below the bottom of the asins.

3. QUALITY OF SECONDARY SEWAGE EFFLUENT AND RENOVATED WATER

eekly samples were taken of the sewage effluent as it entered the infiltration basins. Samples were also taken at distances of 150, 225, and 00 m from the inlet end of the basins, and also at the outlet end of the 50 m-long basins. Renovated water was sampled bi-weekly from the 23 m-deep North and South Wells, the Center Well (perforated from 30 to 55 m), nd from the 18, 24, and 30-m deep wells near the center of the project. he samples were analyzed for free chlorine (effluent only), NH_4-N, NO_3-N, NO_2-N, organic N, PO_4-P, total organic carbon, and fecal coliforms. Identification of trace organics and their concentrations are reported in he next section.

The effluent entering the basins contained 0.27 mg/ℓ total chlorine (Table) from an original dose of 1.5 mg/ℓ at the treatment plant. Chlorine ould not be detected in the rest of the basin. Thus, residual chlorine levels were very low and could not be expected to have an effect on the microbiological processes in the soil below the infiltration basins. itrogen transformations and organic carbon removal in the soil thus were about the same as for the unchlorinated effluent.

he total nitrogen concentration of the effluent entering the basins veraged 17.9 mg/ℓ, of which most (15.4 mg/ℓ) was in the ammonium form (Table 3). The concentration of organic N was 2.4 mg/ℓ. Nitrogen con-entrations of the individual samples are shown in Figure 5. Some nitrifi-ation occurred in the infiltration basins themselves, as indicated by the increase of NO_3-N and the decrease in NH_4-N as the effluent flowed through the basins (Table 3). The average total-N concentration of the renovated ater pumped from the Center Well was 3.73 mg/ℓ (Table 3), indicating a itrogen removal of 79%. This is more than the 69% removal obtained in 1980 with unchlorinated effluent. Thus, the chlorination had no adverse ffect on the transformation and removal of nitrogen in the soil-aquifer ystem. Most of the nitrogen in the renovated water was in the nitrate form (3.4 mg/ℓ for the Center Well). Since the Center Well pumps from a epth of 30 to 55 m, NO_3-peaks were essentially damped out (Figure 6). owever, NO_3-N concentrations in the renovated water from the shallow 18-m well showed the distinct NO_3 peaks as water that had infiltrated at the beginning of a flooding period reached the intake of the well (Figure 7). he 18-m Well is completely cased and open only at the bottom. Thus, it ields renovated water after it has arrived from the vadose zone and joined the aquifer. The average residence time of the infiltrating water in the adose zone and the upper part of the aquifer, as calculated from the ccurrence of the nitrate peaks in the renovated water from the 18-m Well after the start of a new flooding period, is five days. This is for about 10 m of travel through the vadose zone and another 7 m in the aquifer, ielding an average macroscopic velocity of 17/5 = 3.4 m/day. The infiltration rates at the beginning of the floowing periods in Basins 2 and 3 averaged about 0.8 m/day. Thus, the average water content in the vadose zone and upper portion of the aquifer can be calculated as 0.8/3.4 = 0.24 or 24% by volume.

Concentrations of PO_4-P averaged 5.42 mg/ℓ in the secondary effluent entering the basins and 4.1 mg/ℓ of the effluent at the basin outlets (Table 3). Thus, there was some reduction of PO_4-P in the basins them-selves, possibly due to algae uptake or to precipitation as calcium phosphate due to the high pH as algae exhausted the dissolved CO_2 in the water during periods of maximum photosynthetic activity. PO_4-P concentrations in the renovated water from the Center Well averaged 0.72 mg/ℓ, indicating a phosphate removal of 87%. PO_4-P concentrations in the individual samples of the secondary effluent and the renovated water from the Center Well are shown in Figure 8. PO_4-P concentrations in the renovated water were higher for the 18-m Well in the center of the project and decreased for the deeper wells in the center (24- and 30-m Wells) and for the North and South Wells which are on the edges of the basin area (Table 3). Thus, phosphate continued to be removed from the water as it flowed through the aquifer.

Total organic carbon (TOC) concentrations in the effluent increased slightly (from 11.7 to 13.6 mg/ℓ) as the effluent flowed through the basins (Table 3). This increase is probably due to the growth of algae and other biological activity in the basins. Average TOC concentrations of the renovated water ranged from 2.3 and 3.1 mg/ℓ for the South and North Wells to 3.5 and 3.7 mg/ℓ for the 24- and 18-m Wells in the center, respectively. The average TOC concentration for these four wells thus was 3.15 mg/ℓ, yielding an average TOC removal of 73%. Comparing TOC concentrations in the effluent and in the renovated water from the North Well and the 18-m Well (the only two wells for which TOC was determined in both 1980 and 1981), shows that the removal percentages in 1981 with the chlorinated effluent were identical to those in 1980 when the effluent was not yet chlorinated (Table 4). Thus, chlorination had no effect on TOC removal in the soil-aquifer system.

Fecal coliform concentrations averaged 3500/100 mℓ in the secondary effluent entering the basins and 0.27/100 mℓ in the renovated water from the Center Well. These figures compare with 1.3×10^6/100 mℓ and 24/100 mℓ, respectively, in 1980 when the effluent was not yet chlorinated. Thus, the chlorination had a beneficial effect on fecal coliform concentrations. Since virus concentrations in the renovated water were already very low in 1980 for the unchlorinated effluent (i.e. 1 PFU/100 ℓ), viral assays were not repeated in 1981 for the chlorinated effluent.

4. TRACE ORGANICS

Weekly samples of the chlorinated secondary effluent taken at various parts in the infiltration basins, and bi-weekly samples of the renovated water from various wells were taken in the period April-June 1981, and shipped to Stanford University (Environmental Engineering and Science Program, Civil Engineering Department) in California for identification of trace organics. The compounds and their concentrations were then compared to those found in the two-month sampling period in the Fall of 1981 when the effluent was not yet chlorinated, to evaluate the effects of chlorination on trace organics in effluent and corresponding renovated water. A complete report on this study will be issued by Stanford University in the spring of 1982. Main results will be presented here.

The concentrations of organic compounds in the samples were quantified with two gas chromatographic procedures: volatile organic analysis (VOA) and closed-loop stripping analysis (CLSA). Three times during each of the two study periods (Period 1 for the unchlorinated effluent and Period 2 for the chlorinated effluent), additional samples were collected for total organic halogen (TOX) determination, hexane-ether solvent extraction analysis (HEA), base-neutral solvent extraction analysis (BNSEA), and acid-phenol solvent extraction analysis (APSEA). These procedures allowed identification of organic priority pollutants through gas chromatography/mass spectrometry (GC/MS) and permitted additional characterization of the organic constituents in the wastewater and in the renovated water. Since organics concentrations in treated wastewater tend to follow log-normal rather than normal distributions the results were interpreted with log-normal statistics. For each site and organic constituent, the geometric mean and spread factors were computed. The spread factor is similar to the standard deviation for normally distributed data. One standard deviation above or below the geometric mean is obtained by multiplying or dividing, respectively, the geometric mean by the spread factor.

Halogenated organic substances detected by VOA and CLSA in the basins and their concentrations during Periods 1 and 2 are compared in Table 5. The compounds formed were similar to those found in other secondary municipal wastewater. Trichlorophenol, pentachlorophenol, phenanthrene, and diethylphthalate were the only additional priority pollutants identified by the HEA, BNSEA, and APSEA procedures. The data indicate that chlorination resulted in a higher chloroform concentration and in the formation of the three brominated trihalomethanes. Otherwise, chlorination of the secondary wastewater had little effect on the chlorinated organic concentrations measured specifically by these procedures. Several of the chlorinated compounds actually had lower average concentrations during Period 2 than in Period 1. A similar comparison between Periods 1 and 2 for the nonhalogenated aliphatic and aromatic hydrocarbons detected in the basin water (Table 6) indicates some compounds had concentrations that were higher in Period 2, others remained the same, and some had lower concentrations. This suggests that differences in concentrations between Periods 1 and 2 were the result of normal concentration fluctuations in the secondary wastewater, rather than from effects of chlorination.

A paired comparison of the basin inflow and outflow concentrations of the more volatile organic micropollutants (Table 7) indicates a concentration decrease between 30 and 70 percent as water moved across the basins. The data from Periods 1 and 2 were combined to estimate the percent decrease across the basins because of the insignificant concentration differences between the two periods noted previously. Based on log-normal statistics and a Student's t-test comparison, the significance level for the differences between basin inflow and outflow concentrations are given. Values of 0.05 or less indicate that the differences are highly significant. Many of the organic compounds measured by the VOA and CLSA procedures have Henry's Law constants greater than 10^{-3} atm $m^3 mol^{-1}$ and are easily air stripped from wastewater. Hence, volatilization is the likely mechanism that was responsible for the decreases in concentration observed. No difference in the percent decrease between the aromatic and aliphatic compounds shown was observed. Results on the behavior of organic substances during soil passage are shown in Table 8 for Period 1 and in Table 9 for Period 2. Similar data are shown for the nonhalogenated compounds in Tables 10 and 11, respectively. The average basin concentration and spread factor for each compound is listed. Percentage decrease between the average basin concentrations and monitoring well values are also included. Levels of significance for the differences between basin and well concentrations based on a Student's t-test comparison are given. Reductions of trichlorophenol, pentachloro-phenol, pentachloroanisole, phenanthrene, and diethylphthalate with soil passage could not be treated statistically because of insufficient data.

Nonhalogenated hydrocarbons (Tables 10 and 11) decreased (50 to 99 percent) during percolation through the soil with concentrations in the renovated water being near or below the detection limit. However, most of the compounds could still be detected in the renovated water. Reduction percentages were generally higher during Period 2 as a result of higher basin concentrations observed for many of the nonhalogenated compounds. These compounds are subject to microbial decomposition and, presumably, were removed during soil percolation by this process. The additional underground travel between the 18-m and 30-m Wells and North Well did not result in further removal, suggesting that sorption processes had reached steady-state.

The halogenated organic compounds generally decreased to a lesser extent with soil passage. Of the halogenated aliphatic hydrocarbons, the renovated water concentrations of chloroform and 1,1,1-trichloroethane were lower than those in the basin water during Periods 1 and 2. The brominated trihalomethanes present in the secondary wastewater with chlorination were not detected in the renovated water samples. This may have been the result of slow transport due to sorption or chemical or biological transformation. The concentrations of trichloroethylene and pentachloroanisole were significantly higher in the renovated water than in the basin during both sampling periods. Tetrachloroethylene exhibited a similar concentration increase in Period 1 but not in Period 2 except at the South Well. The chlorinated aromatics appeared to be relatively refractory and mobile in the ground showing much less concentration decrease compared with nonchlorinated aromatic hydrocarbons. Less decrease in the dichlorobenzenes was observed in Period 2 than in Period 1. Complete breakthrough appeared to occur for the chlorophenols, but concentrations were near detection limits so that positive conclusions could not be made. The longer percolation distance between the 18-m and 30-m Wells and to the North Well did result in decreased concentration for some of the chlorinated compounds. A combination of biodegradation and sorption processes might have been responsible for the decreases observed. Decreases in the concentrations of the nonhalogenated priority pollutants were comparable to those for the other nonhalogenated aliphatics and aromatic hydrocarbons (Tables 10 and 11).

With the high organic loading during infiltration, it is likely that most of the soil profile at that time was anoxic except for a small aerobic zone at the soil surface. This was shown in laboratory-scale soil columns operated under similar conditions. Dissolved oxygen in the monitoring wells was also below 0.5 mg/ℓ. Chlorinated benzenes and aromatic hydrocarbons have been found to be biodegradable under aerobic, but not anaerobic conditions. Hence, the poor removal of chlorinated aromatics may have resulted from the anoxic conditions in most of the aquifer. However, halogenated one- and two-carbon aliphatic compounds have been found to be degraded under anaerobic, but not aerobic conditions. Thus, biodegradation may have been responsible for the decrease in the concentrations observed for chloroform, 1,1,1-trichloroethane, and brominated trihalomethanes during soil percolation. Samples were analyzed for nitrogen species and results indicated nitrate was present in the renovated water from nitrification of ammonia (average 15.6 mg/ℓ NH_4-N) during soil percolation. Although most of the aquifer was anoxic, conditions with nitrate available were not very reducing and this may explain why complete removal of chloroform and other chlorinated aliphatics did not occur as might otherwise be expected.

Concentrations measured in samples of secondary effluent entering the basins collected in the morning were generally higher than in those taken in the afternoon on the same day. These daily fluctuations were similar in magnitude to variations in the weekly data. For some of the basin water samples, concentrations at the basin midpoint were higher than at the inlet. Such observations were likely the result of sampling procedures. The three basin locations were sampled at nearly the same time, so water at the basin midpoint entered the basin earlier in the day and may have contained higher organic concentrations.

The variability of the influent concentrations may explain the higher average concentrations of tetrachloroethylene and trichloroethylene observed in the renovated water than in the basin water. An insufficient number of samples may have been collected to accurately compute average concentrations in the effluent sampled from the basins and in the renovated water. Tetrachloroethylene concentrations at the 18-m and 30-m Wells were higher at the start of Period 1, possibly from previous infiltration of water with high concentrations, and decreased to secondary effluent concentrations at the end of Period 1 and throughout Period 2. On the other hand, trichloroethylene concentrations were consistently higher in the renovated water compared to the effluent water. Trichloroethylene is a proposed intermediate in the degradation of tetrachloro-ethylene. Hence, the increased trichloroethylene concentrations observed with soil passage may have resulted from bacterial and/or chemical transformation. There is some evidence that bacteria can transform pentachlorophenol to pentachloroanisole in soils. This might account for the increase in pentachloroanisole concentrations observed in the renovated water, but the low concentration of pentachlorophenol in the basin water does not support this conclusion. Further study of these aspects is needed. Uncertainty in the pentachlorophenol concentrations exists because of inaccuracies in the quantitative response factor.

A summary of the organic micropollutants found in the sewage effluent in the basins and in the renovated water from the 30-m Well during Period 1 (Figure 9) qualitatively illustrates the decreased concentrations found with soil percolation. Data from Period 2 show comparable behavior. The concentrations in the basins ranged from 5 μg/ℓ to the detection limit. All of the compounds with average concentrations greater than 0.2 μg/ℓ in the renovated water were chlorinated. Those compounds below 0.2 μg/ℓ in concentration and near the detection limit were mostly nonchlorinated. Thus, the nonchlorinated organics were removed with higher efficiency than the chlorinated organics during soil percolation.

Concentrations of o-dichlorobenzene in Period 1 have been placed on a cross-section of the system (Figure 10) to show penetration of this compound into the subsurface environment below the basins. Contour lines of equal concentration suggest deep vertical penetration to at least 35 m and gradual movement from south to north in the direction of the groundwater gradient.

Concentration variations in the renovated water were less than those in the sewage effluent in the basins. Thus, percolation through the soil had the effect of damping fluctuations in concentrations and eliminating extreme values. This is indicated in Figure 11 which shows the geometric mean (M) and standard deviation (MS and M/S), based upon a log-normal distribution, for o-dichlorobenzene in the basin water and in the renovated water from the monitoring wells during Period 1. The horizontal scale indicates relative travel distance from basins 2 and 3 to the various monitoring wells. The reduction in the standard deviation range in the renovated water samples is a measure of the variation reduction. The 95 percent confidence interval is smaller for the basin water because of the larger number of samples collected. The predominant mechanism for this smoothing of concentration fluctuations is believed to be sorption and desorption in combination with hydraulic dispersion.

The measured TOX data are summarized in Table 12. The basin water TOX was significantly higher with chlorination (Period 2). However, the renovated water TOX concentrations were similar for the two periods. In Period 1, there was a 30 percent lower TOX concentration in renovated water collected from the Center Wells, and the TOX concentration was 55 percent lower in the renovated water from the North and South Wells. In Period 2, the TOX concentration was 56 percent lower at the Center Wells, and 67 percent lower at the North and South Wells. The ratio of TOX to TOC was higher in the groundwater compared to the basin wastewater samples, implying that the halogenated organic compounds comprise the more refractory and mobile portion of the TOC.

In addition to the halogenated aliphatics and aromatics mentioned, other priority pollutants detected in the samples included ethylbenzene, naphthalene, diethylphthalate, and phenanthrene. Other compounds tentatively identified in organic extracts of the basin and renovated water samples using gas chromatography/mass spectrometry were: fatty acids, resin acids, clofibric acid, alkylphenol polyethoxy carboxylic acids

(APECs), trimethylbenzene sulfonic acid, steroids, n-alkanes, caffeine, Diazinon, alkylphenol polyethoxylants (APEs), and trialkylphosphates. Several of the compounds were detected only in the basin water and not in the renovated water. A few others, Diazinon, clofibric acid, and tributylphosphate, decreased in concentration with soil passage, but were detected in the renovated water. The APEs appeared to undergo rather complex transformations during ground infiltration. They appeared to be completely removed with soil percolation during Period 1, but during Period 2, two isomers were found during soil passage while others were removed. Further study on the degradation and mobility of these compounds is needed to understand their behavior in the soil infiltration system.

II. COLUMN STUDIES

The deep alluvial deposits in the valleys of the Basin and Range Province of the southwestern United States are quite heterogeneous. Geologic profiles consist of layers of clay, silt, sand, gravel, boulders, and semi-indurated conglomerate in irregular fashion. Thus, these materials are a far cry from the uniform sand or glass-bead models that have been used to study and predict downward unsaturated flow and convective transport of pollutants.

Groundwater in these areas often is a major source of irrigation water. Deep percolation return flow from the irrigated fields to the underlying aquifer not only is a source of groundwater recharge but also of groundwater contamination. In addition to the salts applied with the irrigation water, the deep percolation water contains fertilizer residues (mostly nitrates) and traces of pesticides, herbicides, and other agricultural chemicals. Since the groundwater in these areas is increasingly used for municipal water supplies, cities have to know what quality trends to expect, what quality monitoring must be done, and what treatment may be necessary in the future.

Where groundwater is deep (several hundred feet, for example, it may take decades for the deep percolation water to move from the root zone to the underlying groundwater. Some of the pesticides and other organics in the deep percolation water may travel much slower than the water itself due to adsorption and other immobilization in the soil materials of the vadose zone. Thus, it may be decades or centuries after the start of an irrigation project before groundwater contamination manifests itself. For this reason, early prediction of groundwater quality trends below irrigated areas is very important. If present agricultural practices appear to have unfavorable long-term effects on groundwater quality, remedial measures can be instituted immediately and municipalities contemplating use of such groundwater for public water supplies can develop strategies for quality monitoring and for possible treatment of the water.

1. COLUMN CONSTRUCTION AND MATERIALS

To study the effect of rock or boulder zones on the downward movement of water and pollutants in the vadose zone, a column 3.35 m long and 1.24 m in diameter was set up in the laboratory. The column was filled with clean sand (average particle size 0.27 mm) and boulders averaging 20 x 15 x 6 cm in size. The boulders were arranged in horizontal layers with the sand in between. The initial objectives of the study were to relate the hydraulic properties (saturated and unsaturated) and the dispersion coefficients of the entire medium to those of the sand alone and to the rock matrix. Another objective was to see how deep-percolation fluxes can be evaluated from neutron-probe water content measurements and downward velocities of conservative tracers. Such a technique could be used in the field, even for gravelly materials, and could be important in the evaluation of local deep percolation rates.

laboratory column consisted of a section of corrugated metal culvert. The culvert was placed in a dry sump located in the old hydraulics laboratory in the main building of the U. S. Water Conservation Laboratory. The top of the column extended 30-cm above the floor level. The bottom of the column was placed in a sheet-metal tray and sealed with silicone sealer. All joints and rivets in the metal culvert were also sealed with the silicone sealer. Next, a 5-cm steel neutron access tube was placed in the center of the column. An 8.8-cm drainage layer of 2.3 cm gravel was placed at the bottom of the column (Fig. 12) to collect all the water draining from the column. A 5-cm diameter perforated aluminum tube was placed horizontally at the bottom of this drainage layer to discharge the drainage water through the outflow opening. The drainage layer was covered by successively finer gravel and sand layers (Fig. 12) to form a graded drainage layer with a total thickness of 32 cm below the actual sand-boulder matrix in the column. To permit sampling of the water as it left the sand-boulder column, a sloping trough was placed at the top of the graded drainage layer, immediately below the sand-boulder matrix (Fig. 12). The trough was 10-cm wide, V-shaped, and equipped with a drainage tube in the bottom of the V for rapid transmittal of the water to the outlet end. The samples collected from this trough were used in tracer-breakthrough studies to evaluate longitudinal dispersion coefficients.

The boulders for the column were selected from the Salt River bed. The main boulder types and corresponding densities were:

Boulder No.	Boulder Type	Density
1	Purple quartzite	2.75
2	White quartzite	2.63
3	Diorite	2.69
4	Arkosic quartzite	2.41
5	Granite	2.63

Boulder No.	Boulder Type	Density
6	Metabasalt	2.46
7	Geronimo head tuff	2.33
8	Granite	2.48
9	White quartzite	2.61
10	Arkosic quartzite	2.45
11	Basalt	2.65
12	Basalt	2.89
13	Orthoquartzite conglomerate	2.64
14	Quartz monzonite	2.38
15	Geronimo head tuff	2.60
16	Diorite	2.85
17	Grey quartzite	2.44
18	Arkosic quartzite	2.34
19	Granite	2.64
20	Schist	2.68

The boulders were numbered, weighed, measured for major and minor diameter and height, and classified into one of the 20 types listed above for density estimation. The volume of each boulder was then calculated from the weight and the estimated density.

The column was packed by alternating layers of sand and boulders. The weight of sand and boulders was determined for each layer. The boulders were placed on top of the sand and "seated" into the sand. The average thickness of each sand-boulder layer was 8.6 cm. The average thickness of the boulders was 6.2 cm. Thus, the average thickness of the sand layer between the boulder layers was 2.4 cm. A Polaroid photograph was taken after each boulder layer was in place (examples are shown in Figure 13). The number of each boulder was then recorded on a xerox copy of the photograph. The average volume of boulders in each layer was determined along with the average size and weight. The hydraulic conductivity of the sand in each layer was determined from separate samples in constant-head permeameter tests. The weight of sand and boulders, the average length, width, height, density, and volume of the boulders, and the hydraulic conductivity K of the sand are shown for each layer in Table 13. The finished column contained a total of 1378 boulders. The column was covered with a 4.5-cm layer consisting of coarse sand at the bottom grading into 1.25-cm gravel at the top.

Six sets of four tensiometers were installed at 40 to 50-cm intervals throughout the column. The tensiometers consisted of ceramic cups with a bubbling pressure of one bar. The cups were 1 cm in diameter and 5 cm in length. Two short lengths of 1/8-in. copper tubing were cemented into the ceramic cups with epoxy. One length extended to the bottom of the ceramic cup and the other just into the top. Both pieces of copper tubing were connected with plastic tubing that went through a rubber stopper in the column wall. The plastic tube connected to the long copper tubing was clamped off and was used only to push air out of the ceramic cup. The plastic tube connected to the short copper tube was attached to a manometer. Of each set of four tensiometers, two were situated above a boulder layer and two were below. One cup of each pair was positioned above a boulder and one was positioned between boulders as shown in Figure 12. A tensiometer was also placed at the bottom of the lowest sand layer of the sand-boulder column and at 1 cm below the top of the uppermost sand layer. The location of the tensiometers is shown in Table 14.

Water contents in the column were determined with the neutron attenuation method, using a Troxler probe. Several neutron measurements were taken in the dry column to obtain a zero water content reading. For the initial infiltration of water into the column, the surface was ponded with 12 cm water. Water content measurements were made continuously at 10-cm depth intervals within the wetted zone. The amount of water applied was measured by water meters and by measuring the drop of water level from a supply reservoir. At any time, the amount of water added to the column was known. The neutron method was then calibrated by relating the count rate to the amount of water in the column when the wetting front reached the bottom. Thus, two calibration points were obtained: one at zero water content and one near saturation. The resulting calibration equations were $\Theta = 0.4188R - 0.0453$ for Troxler probe No. 23653, and $\Theta = 0.3702R - 0.0441$ for Troxler probe No. 904, where Θ is the volumetric water content and R is the ratio of the measured count rate to that for the standard water bucket.

2. HYDRAULIC CONDUCTIVITY RELATIONS

Four different infiltration rates were used. The first rate was under ponded conditions with a 12-cm head. Constant water level above the column was maintained with a float valve. During the 21 days of ponding, the infiltration rate increased from 2.5 m/day when the wet front had just reached the bottom of the column to a relatively constant 3.2 m/day toward the end of the period. The increase in infiltration rate was associated with an increase in water content and a lower hydraulic gradient in the upper portion of the column. Final hydraulic gradients were 0.63 in the top 110 cm and 1.26 in the remainder of the column. The total-head profile is shown in Fig. 14 for the different flow rates. The pressure head above the boulders was about 0.5 cm higher than the pressure head between the boulders. The water content in the top 110 cm averaged 0.215, which is essentially saturated, since the porosity of the column was 0.218. The corresponding hydraulic conductivity K was 5.1 m/day. The water content below 120 cm averaged 0.185, and the corresponding K was 2.6 m/day. The lower zone could be considered "resaturated" as compared to the essentially complete saturation in the top zone. The ratio of the saturated to resaturated K-values was about 2, which agrees with values reported in the literature. The movement of the wetting front down the column during the initial saturation is shown in Fig. 15.

After the ponded-infiltration test, the infiltration rate was reduced to 140 cm/day. This rate was maintained with a network of drip irrigation tubing. A total of 24 m of double-chamber polyethylene tubing was laid on top of the column. The openings in the tubing were 20 cm apart. The flow rate was controlled by a pressure regulator at the 140-cm/day rate. The next infiltration rate was set at 32 cm/day, using the same network of drip-irrigation tubing but replacing the pressure regulator by a positive displacement pump to control the flow rate. The last infiltration rate was set at 2 cm/day. To maintain this rate, the drip irrigation tubing was removed and water was applied with a Technicon sampling pump that created a flow rate of 0.42 mℓ/min in each of a total of 40 pump tubes that were placed to distribute the water uniformly over the column surface. Water contents, pressure heads, and inflow and outflow rates for the column were measured at each flow rate until constant. As could be expected, the equilibrium hydraulic gradients in the column were equal to one for all unsaturated flow systems. Therefore, the unsaturated K-values were equal to the infiltration rates. The resulting hydraulic conductivity-water content and hydraulic conductivity-pressure head relationships are shown in Figure 16.

The water content profiles in the column for the different infiltration rates and after drainage for 37 days when outflow had essentially ceased are shown in Figure 17. The water content-pressure head relation-ship for the sand-boulder medium was obtained from the neutron measurements and tensiometer readings and is shown in Figure 18. The points in this graph represent all tensiometers and flow rates, including drainage. Under the saturated conditions in the upper part of the column when water was ponded, pressure heads greater than zero were plotted at zero.

The water content-pressure head (Θ-h) relationship for the sand only was measured on separate samples with small pressure cells and is shown in Figure 19. The relation between the unsaturated hydraulic conductivity and Θ of the sand only was calculated from the Θ-h data and the average K of the sand at saturation (8.8 m/day), using Millington and Quirk's method. The relationship is shown in Figure 20.

An additional check on the neutron calibration was made when the infiltration rates were changed. The change in storage as determined from the water content measurements should be the same as the difference between the inflow and outflow during the change in infiltration. As shown in Table 15, the values were in close agreement.

EFFECT OF BOULDERS ON HYDRAULIC CONDUCTIVITY

The hydraulic conductivity of a sand-rock mixture is less than K of the sand alone because of the reduced void space due to the presence of the boulders. To investigate the relation between hydraulic conductivity and reduction in void spaces, permeability tests were run on different mixtures of the sand and 1.5-cm diameter rock. The amount of rock added was varied from 0 to 70% by weight. At higher rock contents, the voids between the rocks were no longer completely filled with sand. As could be expected, K decreased with increasing rock content. The decrease in K was essentially linear with the decrease in void ratio (volume of voids divided by volume of solids), of the sand-rock mixture, as shown in Figure 21. Thus, K_m of the mixture could be expressed as

$$K_m = K_s \frac{e_m}{e_s} \tag{3}$$

where

e = void ratio, and
s & m = subscripts for sand alone and sand-rock mixture, respectively.

The void ratio of the sand-boulder column was 0.28 and that of the sand alone was 0.72. Since K_s = 8.81 m/day, equation 3 shows that K_m of the column should be 3.4 m/day. This value is between the saturated and resaturated K-values of 5.2 and 2.6 m/day, respectively, as calculated from infiltration rate and hydraulic gradients in the column. Thus, eq. 3 gives a reasonable estimate of K in vertical direction for the sand-boulder column.

4. DISPERSION COEFFICIENTS

The longitudinal dispersion coefficient of the column was determined at each flow rate by applying a salt tracer to the infiltrating water and measuring the breakthrough curve of the salt in the column outflow. A sodium chloride solution containing 1000 mg/ℓ of chloride was applied continuously with the inflowing water. The outflow samples were obtained from the trough located just below the bottom sand layer. Samples were taken until the salt concentration C in the outflow was the same as the salt concentration C_o in the inflow. Breakthrough curves are shown in Figure 22 for the four different flow rates. The dispersion coefficient (D_K) was calculated from the equation presented by Kirkham and Powers (1972) as

$$D_K = vL/4\pi s^2 \tag{1}$$

where v = macroscopic velocity in column,
L = length of column, and
s = slope of breakthrough curve when the salt concentration of the outflow is one-half that of the inflow (C/C_o = 0.5).

Values of D_K are shown in Table 15 for the different infiltration rates.

Dispersion coefficients can also be calculated from breakthrough curves of continuously applied tracers with Brenner's Peclet Number B_r. The breakthrough curve is matched to type curves with various values of B_r, then $D_B = vL/4B_r$. The values of D_B from the Brenner numbers are also shown in Table 15 and are essentially the same as D_K from Kirkham and Powers method.

D_K was also determined from the breakthrough curve of a slug application f tracer added to the inflow for the ponded condition. For this urpose, a 2-cm depth of water containing 1000 mg/ℓ nitrate was applied to the top of the column during infiltration. Breakthrough curves from slug applications of a tracer are like probability curves. The resulting curve (Figure 23) indeed represented a probability curve, except for some irregularities at the beginning which were attributed to "experimental error". The dispersion coefficient D_K was calculated rom the breakthrough curve with the equation presented by Kirkham and owers (1972) as

$$D_K = \frac{vL\ (X_o/n2L)^2}{2\ (1 + X_o/n2L)Z^2} \qquad (2)$$

here X_o = amount of water in which slug was contained (expressed as depth),
n = porosity of medium (Θ if unsaturated), and
Z = factor obtained from normal distribution table.

The other terms are as defined for equation 1.

To find Z, the maximum value of C/C_o of the breakthrough curve is determined. Dividing this value by 2 gives the normalized area under the robability curve. The corresponding Z-value is then obtained from ables such as "Normal Curve of Error" in the Handbook of Chemistry and Physics. This procedure yielded a D_K of 0.68 m^2/day, as compared to 0.82 ^{2}/day (Table 15) calculated from the breakthrough curve of the coninuous tracer.

Theoretically, C/C_0 should be 0.5 when one volume of pore fluid has assed through the column. For the breakthrough curves in Figure 22, the pore volumes at C/C_0 = 0.5 were between 0.98 and 1.0. This means that the average macroscopic velocity in the column was essentially equal to he Darcy velocity (infiltration rate) divided by the volumetric water ontent. This relation between macroscopic and Darcy velocity, which is comonly accepted for saturated, homogeneous media, thus also held for the sand-boulder medium, saturated as well as unsaturated. The relation $_m = V_d/\Theta$ thus enables calculation of retention times of deep percolation water in vadose zones and prediction of arrival times of deep percolation water and pollutants at the underlying groundwater.

The relationship between the dispersion coefficient and the macroscopic velocity is shown in Figure 24. The points are close to the linear relaionship indicated by theory. The ratio of dispersion coefficient to acroscopic velocity is the dispersivity, which for the sand-boulder medium was 0.043 m.

he 2-cm/day flow rate through the column was not large enough to form positive pressures in the sampling trough. Thus, samples had to be taken from the outflow at the bottom of the culvert. Because of the large volume of water stored in the gravel drainage layer below the sand-boulder column, the tracer in the outflow was diluted and the samples showed reduced concentrations, as shown by the trailing off of the curve in Figure 22. Thus, a valid breakthrough curve could not be obtained for this infiltration rate.

The dispersion coefficient of the sand alone was evaluated separately as 0.093 m^2/day, using a 95-cm column and continuous application of a tracer. The pore velocity in the sand was 37.3 m/day. Thus, the dispersivity of the sand was 0.093/37.3 = 0.0025 m.

5. PULSE APPLICATION

When the outflow had essentially stopped after the column was allowed to drain for 37 days, a 2-cm pulse of water was applied to the column and the water content was monitored with time. The advance of the wetting front of the pulse is shown in Figure 25. The pulse could easily be picked up in the early stages. However, as time went on, the pulse flattened out and became very difficult to distinguish at greater depths and times.

SUMMARY AND CONCLUSIONS

23rd Avenue Project

Operation of the 23rd Avenue rapid-infiltration project was continued until 1 July 1981 to determine how chlorination of the treatment plant effluent affected trace organics in the effluent and in the resulting renovated water as pumped from the underlying aquifer. The treatment plant began to chlorinate its effluent on 1 December 1980. The pre-chlorination conditions were analyzed in the fall of 1980, when effluent and renovated water were sampled for trace organics analyses for about two months. Another period of sampling for trace organics analysis was held from April until 1 July 1981. Comparing the results for the post-chlorination period with those obtained prior to chlorination would indicate the effect of chlorination on trace organics in sewage effluent and renovated water. This effect must be known to determine the suitability of chlorinated effluent for groundwater recharge with a rapid infiltration system, and the need for a dual outfall system to separate the chlorinated effluent for general discharge from the unchlorinated effluent to be used for rapid infiltration. Weekly samples of sewage effluent from the basins and of renovated water from the aquifer were shipped to Stanford University's Civil Engineering Department (Environmental Engineering and Science Program) for trace organics analysis. Flooding and drying periods were kept at 2 weeks each, as was done in the fall of 1980 when samples were obtained for the unchlorinated effluent situation.

The results showed that chlorination of the secondary effluent, which was done at the relatively low rate of 1.5 mg/ℓ chlorine, had little effect on the organic compounds identified and their concentrations except for the trihalomethanes. Chloroform concentrations increased by 66% and brominated trihalomethanes were detected with chlorination but not without. The small effect probably was due to the ammonium in the effluent (average NH_4-N concentration was 16 mg/ℓ). For both sampling periods, nonhalogenated aliphatic and aromatic hydrocarbons had removals of 50 to 99% during percolation through soil. Halogenated compounds were removed to a lesser extent. Soil passage reduced concentrations of chloroform, 1,1,1-trichloroethane and brominated trihalomethanes by 50% for the unchlorinated effluent, and by 80% for the chlorinated effluent. Trichloroethylene, tetrachloro-ethylene, and pentachloroanisole concentrations for unknown reasons appeared to be higher in the renovated water than in the secondary effluent. Chlorinated benzenes and phenols appeared to be quite mobile in the ground. These compounds showed much less removal (20 to 40%) than nonhalogenated hydrocarbons. The average total organic halogen (TOX) concentration in the secondary effluent was significantly higher with chlorination (142 μg Cl/ℓ than without chlorination (84 μg Cl/ℓ). However, the TOX concentrations in the renovated water were similar during both sampling periods. In passage through the soil, the TOX concentrations decreased 30 to 67%. In addition to the halogenated aliphatics and aromatics mentioned, other priority pollutants detected in the samples included ethylbenzene, naphthalene, diethylphthalate, and phenanthrene. Other compounds tentatively identified in organic extracts of the basin and renovated water samples using gas chromatography/mass spectrometry were: fatty acids, resin acids, clofibric acid, alkylphenol polyethoxy carboxylic acids (APECs), trimethylbenzene sulfonic acid, steroids, n-alkanes, caffeine, Diazinon, alkylphenol polyethoxylates (APEs), and trialkylphosphates. Several of the compounds were detected only in the basin water and not in the renovated water. A few others, Diazinon, clofibric acid, and tributylphosphate, decreased in concentration with soil passage, but were detected in the renovated water. The APEs appeared to undergo rather complex transformations during ground infiltration. They appeared to be completely removed with soil percolation during Period 1, but during Period 2, two isomers were found during soil passage while others were removed. Further study on the degradation and mobility of these compounds is needed to understand their behavior in the soil infiltration system. Volatilization in the basins was an important removal mechanism for the low molecular weight compounds. Between 30 and 70% of the chlorinated benzenes and 1- and 2-carbon halogenated organic compounds were removed in this way. Biodegradation and sorption processes appear to be responsible for the decreased organic concentrations resulting from soil passage. Since many organic contaminants reach the groundwater during rapid infiltration, such systems should be designed to localize the resulting contamination of the aquifer.

The absence of any major effect of chlorinating the effluent on the trace organics in the effluent and in the resulting renovated water probably was due to the low dose (1.5 mg Cl/ℓ) at the treatment plant and to the high ammonium content of the secondary effluent which tied up most of the chlorine and chloramines. Thus, the residual chlorine concentrations of the effluent as it entered the infiltration basins was only 0.27 mg/ℓ.

Chlorination also had no adverse affect on biological processes in the soil-aquifer system below the basins as indicated by identical reductions in total organic carbon concentrations before and after chlorination (i.e. 66% before and 68% after chlorination for the 18-m deep monitoring well in the center of the project and 74% for both pre-chlorination and post-chlorination results for the 23-m deep monitoring well north of the system). Nitrogen removals were even higher for the chlorinated effluent (79%) than for the unchlorinated effluent (69%), so that chlorination had no adverse effect on nitrogen transformations and removal either. Chlorination reduced fecal coliform concentrations in the secondary effluent from 1.3×10^6 to 3500 per 100 mℓ, and in the renovated water from the Center Well from 24 to 0.27 per 100 mℓ. Virus concentrations in the renovated water resulting from the unchlorinated effluent were already very low (about 1 PFU/100 ℓ), so that the virus assays were not repeated for the renovated water from the chlorinated effluent. The results thus showed that chlorination of the effluent is beneficial, and that chlorinated effluent is suitable for use in rapid-infiltration systems.

The depth of the groundwater table in the first six months of 1981 averaged about 10 m. Hydraulic loading rate of the four basins averaged 42 m for the 6-month period. The fourth basin had a much lower infiltration rate (17.1 m for the 6 months) because of standing water during the drying (low spots and leaky gate). Since standing water can be avoided with good construction and maintenance, a design hydraulic loading rate of 100 m/year seemed reasonable. For the 16-ha system of the project, this corresponds to a hydraulic capacity of about 13,000 acrefeet per year or 11.6 million gallons per day.

The total nitrogen concentration of the sewage effluent entering the infiltration basins averaged 17.9 mg/ℓ, of which 15.4 mg/ℓ was in the ammonium form. The total nitrogen concentration in the renovated water from the Center Well was 3.73 mg/ℓ, of which 3.38 mg/ℓ was in the nitrate form. This is well below the maximum limit of 10 mg/ℓ for drinking and it is even in the range of 0-5 mg/ℓ where, according to California irrigation water quality standards, there are no adverse effects of the nitrogen on crop yield or quality when the water is used for irrigation. The average concentrations of PO_4-P were 5.4 mg/ℓ in the secondary effluent and 0.72 mg/ℓ in the renovated water from the Center Well, yielding a removal of 87%.

On June 30, the basins were dried for cleaning and maintenance. This date also marked the completion of the U.S. Water Conservation Laboratory's research at the 23rd Avenue project. The research results over the years have shown that the renovated water from the project meets public health, agronomic, and aesthetic criteria for unrestricted recreation and for primary-contact recreation, and that chlorination of the treatment plant effluent has no adverse affect on the operation of the system or on the quality of the resulting renovated water. Chlorination was beneficial in that it reduced fecal coliform concentrations in the effluent and in the renovated water. Because the renovated water contains a wide spectrum of chlorinated and other organic compounds at very low concentrations, it should not be used for public water supplies without activated carbon filtration or similar treatment (plus, of course, disinfection), and it should not be allowed to move uncontrolled in the aquifer system. This requires a system of interceptor or collector wells for pumping the renovated water out of the aquifer.

Column Studies

Downward flow of water in stony vadose zones and the convective transport of contaminants was modeled in a laboratory column 3.35 m long and 1.24 m in diameter. The objectives of the study were to (1) get a better insight into the flow of deep percolation water from irrigated fields to the underlying groundwater, (2) evaluate the effect of gravel and boulder strata on the downward flow, and (3) test measurement techniques for deep percolation rates under field conditions. A total of 1378 boulders of known volume and geometry averaging 20 x 15 x 6 cm in size were placed in the column in horizontal layers with medium sand in between. The position of the boulders in each layer was recorded photographically. The column was ponded with 12-cm water to determine the saturated (or "resaturated") hydraulic conductivity of the sand-boulder medium. Water contents were measured with the neutron method, which was calibrated on the basis of the volume of water applied while the column was wetting up. Pressure heads of the water in the column were measured with tensiometers. After the ponded infiltration, for which a relatively stable flux of 3.2 m/day was reached, infiltration rates were successively reduced to 1.4, 0.32, and 0.02 m/day to produce unsaturated flow at various rates in the column. The infiltration rates were maintained with drip irrigation systems that distributed the water uniformly at the top of the column. From corresponding neutron and tensiometer measurements, the relations between unsaturated hydraulic conductivity, water content, and pressure head of the sand-boulder medium could be determined. These relationships were also determined for the sand alone in separate column experiments for future comparisons of the effect of the boulder matrix on the hydraulic properties of a boulder-sand mixture. Longitudinal dispersion coefficients were determined by continuous and slug additions of conservative tracers (nitrate and chloride) to the infiltrating water and measuring the breakthrough curves of the tracers at the bottom of the column.

The hydraulic conductivity of the column after ponding was 5.2 m/day for the mostly saturated top portion of the column, and 2.6 m/day for the lower portion of the column which still had some entrapped air (i.e. it was "resaturated"). These hydraulic conductivity values agreed with a calculated value of 3.4 m/day obtained by multiplying the hydraulic conductivity of the sand alone by the ratio of the void space in the sand-boulder medium to that in the sand alone. Pore velocities or "macroscopic" downward flow rates in the sand-boulder medium closely agreed with the calculated values obtained by dividing the Darcy flux (infiltration rate or deep percolation rate) by the volumetric water content of the medium. The dispersivity of the sand alone was 0.0025 m and that of the sand-boulder medium was 0.043 m. Thus, the presence of the boulders significantly increased the vertical dispersion of contaminants moving down with the water.

The results of the study will be used in the prediction of bulk hydraulic properties of boulder and gravel strata with sand or other fines between the rocks, and in the development of field procedures for direct measurement of deep percolation rates below irrigated soils.

PERSONNEL: Herman Bouwer, Robert C. Rice, and Gladys C. Auer

Table 1. Average infiltration rates (m/day) in basins during flooding and hydraulic loading (m) in first 6 months of 1981.

Date	Basin 1	Basin 2	Basin 3	Basin 4
01/12-26		0.68	0.59	
01/26-02/09	0.56			0.22
03/02-16		0.83	0.71	
03/16-30	0.59			0.23
03/30-04/13		0.89	0.77	
04/13-27	0.67			0.24
04/27-05/11		0.96	0.88	
05/11-28	0.71			0.25
05/28-06/15		0.72	0.73	
06/15-30	0.62			0.28
Average	0.63	0.82	0.74	0.24
Total Infiltration for first 6 months	43.9 m	57.3 m	51.5 m	17.1 m

Table 2. Average chlorine concentrations (mg/ℓ) in secondary effluent at various points in the infiltration basins for January-June 1981.

Location	Free chlorine	Combined chlorine	Total chlorine
Basin inflow	0.03	0.24	0.27
At 150 m	0.00	0.00	0.00
At 225 m	0.00	0.00	0.00
At 300 m	0.00	0.00	0.00
At outlet	0.00	0.00	0.00

Table 3. Quality parameters in mg/ℓ (average values) for the secondary effluent at various points in the basins and for the renovated water from various wells for January-June 1981.

	Total N	NH_4-N	NO_3-N	NO_2-N	Organic-N	PO_4-P	Total organic carbon	Fecal coliforms/per 100 mℓ
Secondary effluent								
Inflow	17.9	15.4	0.08	0.01	2.44	5.42	11.7	3500
At 150 m	17.2	15.2	0.05	0	1.97	5.18	12.4	
At 225 m	17.0	14.5	0.11	0.03	2.37	4.88	11.3	
At 300 m	15.4	12.7	0.10	0.02	2.56	3.84	13.0	
At outlet	14.1	10.1	0.25	0.03	3.68	4.11	13.6	
Renovated water								
18-m Well	7.50	4.48	2.52	0	0.50	4.42	3.72	2.73
24-m Well	6.55	3.70	2.37	0	0.48	3.70		2.30
30-m Well	6.15	3.12	2.68	0	0.35	3.40	3.52	0.50
Center Well	3.73	0.10	3.38	0	0.25	0.72		0.27
North Well	3.90	0.51	2.95	0.02	0.40	1.40	3.07	0.00
South Well	3.34	0.39	2.62	0	0.33	0.97	2.29	1.07

Table 4. Average concentrations of total organic carbon in effluent and [illegible] water, and TOC removal percentages in 1980 with unchlorinated effl[illegible] and in 1981 with chlorinated effluent.

	1980 unchlorinated effluent		1981 chlorinated effl[illegible]	
Sample	mg/ℓ	% removal	mg/ℓ	% r[illegible]
Secondary effluent	9.34		11.67	
18-m Well	3.17	66.1	3.72	68.[illegible]
North Well	2.45	73.8	3.07	[illegible]

Table 5. Halogenated organic compounds identified during periods 1 and 2 in basin water.

	Concentration, μg/ℓ			
	Secondary Wastewater (Basin Inflow)		Basin Average	
Constituent [a]	Period 1	Period 2	Period 1	Period 2
Halogenated aliphatic hydrocarbons				
Chloroform	2.88	4.79	2.72	3.46
1,1,1-trichloroethane	2.45	1.79	2.94	1.41
carbon tetrachloride	0.13	0.15	0.12	0.12
bromodichloromethane	–[b]	0.51	–	0.26
trichloroethylene	0.91	0.53	0.91	0.39
dibromochloromethane	–	0.46	–	0.23
tetrachloroethylene	2.21	1.82	2.63	1.69
bromoform	–	0.13	–	0.10
Chlorinated aromatics				
o-dichlorobenzene	4.11	3.18	3.52	2.40
m-dichlorobenzene	1.15	0.53	0.79	0.38
p-dichlorobenzene	2.70	2.82	2.25	1.82
1,2,4-trichlorobenzene	0.33	0.44	0.19	0.38
trichlorophenol	0.01	0.02	0.01	0.02
pentachlorophenol	0.02	0.04	0.02	0.04
pentachloroanisole[c]	0.63	0.26	0.43	0.18

[a] Identification confirmed by comparison with standards.
[b] "–" Not detected.
[c] Only compound that is not a priority pollutant.

Table 6. Nonhalogenated organic compounds identified during periods 1 and 2 in basin water.

	Concentration, μg/ℓ			
	Secondary Wastewater (Basin Inflow)		Basin Average	
Constituent [a]	Period 1	Period 2	Period 1	Period 2
Aliphatic hydrocarbons				
5-(2-methylpropyl) nonane [b]	0.49	1.10	0.35	0.5
2,2,5-trimethylhexane [b]	0.15	0.38	0.11	0.1
6-methyl-5-nonene-4-one [b]	0.34	1.51	0.41	0.94
2,2,3-trimethylnonane [b]	0.31	0.64	0.12	0.2
2,3,7-trimethyloctane [b]	0.18	0.40	0.12	0.2
Aromatic hydrocarbons				
o-xylene [a]	0.37	0.50	0.45	0.50
m-xylene [a]	0.73	1.33	0.76	1.0
p-xylene [a]	0.12	0.07	0.17	0.1
C_3 benzene isomer [b]	0.51	0.22	0.56	0.34
C_3 benzene isomer [b]	0.40	0.51	0.48	0.5
styrene [a]	0.15	0.77	0.26	0.5
1,2,4-trimethyl benzene [a]	0.66	0.81	0.80	1.04
ethylbenzene [a+]	0.20	0.09	0.19	0.15
napththalene [a+]	0.17	0.71	0.22	0.6
phenanthrene [a+]	-	0.11	0.10	0.1
diethylphthalate [a+]	20	15	19	10

[a] Identification confirmed by comparison with standards.
[b] Identification based on best mass spectrum fit with National Bureau of Standards Library of Mass Spectra. Concentrations shown are relative to the internal standard.
[+] Priority pollutant.

Table 7. Percentage decrease in organic constituents across infiltration basins using a paired comparison of basin inflow and outflow data.

	Average decrease across basin (Difference betwen basin inflow and outflow)	
	%	Significance level
Chlorinated aliphatic hydrocarbons		
chloroform	31	0.025
1,1,1-trichloroethane	49	0.001
trichloroethylene	39	0.01
tetrachloroethylene	30	0.05
Chlorinated aromatic hydrocarbons		
o-dichlorobenzene	40	0.05
m-dichlorobenzene	65	0.001
p-dichlorobenzene	42	0.025
1,2,4-trichlorobenzene	73	0.2
(chloromethyl)-benzene	65	0.05
Aliphatic hydrocarbons		
2,2,5-trimethylhexane	40	0.20
5-(2-methylpropyl) nonane	51	0.025
2,2,3-trimethylnonane	55	0.05
Aromatic hydrocarbons		
o-xylene	35	0.025
m-xylene	35	0.10
1,2,4-trimethyl benzene	52	0.025
C_3-benzene isomer	53	0.10
naphthalene	22	0.10

Table 8. Percentage concentration decrease in halogenated organic substances by ground infiltration during period 1.

Constituent	Average Basin Concent. (27 samples) Geometric Mean (μg/l)	Spread Factor	18 m Well Decrease (%) (6 samples) Aver.	Significance Level	30 m Well Decrease (%) (6 samples) Aver.	Significance Level	North Well Decrease (%) (6 samples) Aver.	Significance Level	South Well Decrease (%) (6 samples) Aver.	Significance Level
<u>chlorinated aliphatic hydrocarbons</u>										
chloroform	2.72	1.63	61	0.001	68	0.001	74	0.001	71	0.001
1,1,1-trichloroethane	2.94	3.27	34	0.15	49	0.01	31	0.10	61	0.001
carbon tetrachloride	0.12	2.41	0	1.0	0	1.0	-25	0.50	33	0.01
trichloroethylene	0.91	2.04	-180	0.001	-160	0.001	-68	0.001	-9	0.5
tetrachloroethylene	2.63	2.03	-97	0.001	-29	0.2	-57	0.001	9	0.6
<u>chlorinated aromatics</u>										
o-dichlorobenzene	3.52	1.88	25	0.20	34	0.02	40	0.001	53	0.001
m-dichlorobenzene	0.79	2.25	58	0.002	58	0.001	63	0.001	71	0.001
p-dichlorobenzene	2.25	1.60	33	0.002	33	0.002	44	0.001	48	0.001
1,2,4-trichlorobenzene	0.19	1.97	42	0.10	37	0.20	37	0.10	32	0.10
trichlorophenol	0.01	i.d.	0	i.d.	0	i.d.	0	i.d.	0	i.d.
pentachlorophenol	0.02	i.d.	0	i.d.	0	i.d.	0	i.d.	0	i.d.
pentachloroanisole	0.43	i.d.	-150	i.d.	-160	i.d.	14	i.d.	0	i.d.

i.d., Insufficient data for statistical evaluation; values measured by BNSEA and APSEA on two samples.

Table 9. Percentage concentration decrease in halogenated organic substances by ground infiltration during period 2.

Constituent	Average Basin Concent. (36 samples) Geometric Mean (μg/l)	Spread Factor	18 m Well Decrease (%) (6 samples) Aver.	Significance Level	30 m Well Decrease (%) (6 samples) Aver.	Significance Level	North Well Decrease (%) (6 samples) Aver.	Significance Level	South Well Decrease (%) (6 samples) Aver.	Significance Level
halogenated aliphatic hydrocarbons										
chloroform	3.46	1.52	88	0.0001	86	0.0001	87	0.0001	80	0.0001
1,1,1-trichloroethane	1.41	2.45	84	0.0001	85	0.0001	76	0.0001	63	0.0002
carbon tetrachloride	0.12	2.15	42	0.1	58	?	58	?	58	?
bromodichloromethane	0.26	1.91	62	?	62	?	62	?	62	?
trichloroethylene	0.39	2.22	-267	0.0001	-323	0.0001	-154	0.0001	-597	0.0001
dibromochloromethane	0.23	1.94	57	?	57	?	57	?	57	?
tetrachloroethylene	1.69	2.40	31	0.1	1	0.8	4	0.7	-94	0.005
bromoform	0.08	3.35	10	?	10	?	10	?	10	?
chlorinated aromatics										
o-dichlorobenzene	2.40	2.11	10	0.6	21	0.2	-1	0.95	-15	0.5
m-dichlorobenzene	0.38	2.66	5	0.7	29	0.2	0	1.0	-5	0.7
p-dichlorobenzene	1.82	1.86	10	0.5	24	0.1	11	0.5	3	0.7
1,2,4-trichlorobenzene	0.38	1.90	71	0.0001	68	0.0001	61	0.0001	66	0.0001
trichlorophenol	0.02	i.d.	0	i.d.	0	i.d.	0	i.d.	0	i.d.
pentachlorophenol	0.04	i.d.	0	i.d.	0	i.d.	0	i.d.	0	i.d.
pentachloroanisole	0.18	i.d.	-120	i.d.	-83	i.d.	-18	i.d.	-213	i.d.

i.d., Insufficient data for statistical evaluation; values measured by BNSEA and APSEA on three samples.
?, Compound below detection limit, no value can be reported.

Table 10. Percentage concentration decrease of hydrocarbons by ground infiltration during period 1.

Constituent	Average Basin Concent. (27 samples) Geometric Mean (µg/l)	Spread Factor	18 m Well Decrease (%) (6 samples) Aver.	Signif-icance* Level	30 m Well Decrease (%) (6 samples) Aver.	Signif-icance* Level	North Well Decrease (%) (6 samples) Aver.	Signif-icance* Level	South Well Decrease (%) (6 samples) Aver.	Signif-icance* Level
aliphatic hydrocarbons										
5-(2-methylpropyl) nonane	0.35	1.84	94	?	89	0.05	94	0.001	94	0.005
2,2,5-trimethylhexane	0.11	2.49	82	?	82	?	82	?	82	?
6-methyl-5-nonene-4-one	0.41	3.21	93	0.001	90	0.001	95	0.001	93	0.001
2,2,3-trimethylnonane	0.21	2.10	76	0.01	76	0.01	76	0.01	76	0.01
2,3,7-trimethyloctane	0.12	1.90	50	0.05	75	0.01	75	0.01	83	?
aromatic hydrocarbons										
o-xylene	0.45	3.19	67	0.02	69	0.001	69	0.001	73	0.001
m-xylene	0.76	2.43	78	0.001	82	0.001	75	0.001	76	0.001
p-xylene	0.17	2.45	53	0.05	71	0.01	53	0.05	59	0.01
C_3-benzene isomer	0.56	2.91	84	0.001	86	0.001	82	0.001	80	0.001
C_3-benzene isomer	0.48	3.04	85	0.001	88	0.001	90	0.001	90	0.001
styrene	0.26	3.84	92	?	92	?	92	?	92	?
1,2,4-trimethyl benzene	0.80	4.59	78	0.002	84	0.001	84	0.001	83	0.001
ethylbenzene	0.19	2.38	53	0.005	58	0.05	47	0.10	37	0.20
naphthalene	0.22	2.84	68	0.05	82	0.10	86	0.01	91	?
phenanthrene	0.10	i.d.	80	i.d.	80	i.d.	80	i.d.	80	i.d.
diethylphthalate	19	i.d.	20	i.d.	75	i.d.	80	i.d.	95	i.d.

* Values with "?" indicate that groundwater concentrations were below the detection limit of 0.02 µg/l.

Table 11. Percentage concentration decrease of hydrocarbons by ground infiltration during period 2.

	Average Basin Concent. (36 samples)		18 m Well Decrease (%) (6 samples)		30 m Well Decrease (%) (6 samples)		North Well Decrease (%) (6 samples)		South Well Decrease (%) (6 samples)	
Constituent	Geometric Mean (µg/l)	Spread Factor	Aver.	Significance* Level	Aver.	Significance* Level	Aver.	Significance* Level	Aver.	Significance* Level
aliphatic hydrocarbons										
5-(2-methylpropyl) nonane	0.57	1.86	96	?	96	?	96	?	96	?
2,2,5-trimethylhexane	0.18	2.74	89	?	89	?	89	?	89	?
6-methyl-5-nonene-4-one	0.94	2.49	98	0.0001	99	0.0001	99	0.0001	99	0.0001
2,2,3-trimethylnonane	0.25	2.31	92	?	92	?	92	?	92	?
2,3,7-trimethyl octane	0.27	2.30	93	?	93	?	93	?	93	?
aromatic hydrocarbons										
o-xylene	0.50	2.71	88	0.0001	92	0.0001	86	0.0001	86	0.0001
m-xylene	1.00	2.14	98	0.0001	98	0.0001	98	0.0001	97	0.0001
p-xylene	0.12	3.86	92	0.0001	92	?	92	?	92	0.0005
C_3 benzene isomer	0.34	4.46	94	?	94	?	94	?	94	?
C_3 benzene isomer	0.53	2.71	96	0.0001	96	0.0001	96	0.0001	96	?
styrene	0.58	2.39	98	0.0001	98	0.0001	97	0.0001	98	0.01
1,2,4-trimethyl benzene	1.04	3.81	96	0.0001	96	0.0001	98	?	97	0.0001
ethylbenzene	0.15	3.99	67	0.2	93	0.002	80	0.005	87	0.0001
naphthalene	0.63	2.55	91	0.0001	87	0.0001	94	0.0001	83	0.0001
phenanthrene	0.10	i.d.	90	i.d.	90	i.d.	90	i.d.	90	i.d.
diethylphthalate	10	i.d.	90	i.d.	90	i.d.	90	i.d.	90	i.d.

Table 12. Average concentrations of total organic halogen and ratio of TOX in samples collected during periods 1 and 2.

	Total Organic Halogen µg Cl/1		TOX/TOC Ratio mol Cl/mol C	
Location	Period 1	Period 2	Period 1	Period 2
Secondary Wastewater (Basin Inflow)	87	150	0.0032	0.0057
Basin Average	84	142	0.0031	0.0050
18 m Well	65	55	0.0069	0.0059
30 m Well	53	71	0.0065	0.0083
North Well	39	54	0.0054	0.0067
South Well	38	40	0.0053	0.0055

Table 13. Physical data for sand and boulders by layers.

Layer No.	Layer Thickness (cm)	Weight Sand (kg)	Weight Boulders (kg)	Avg. Boulder Dimensions Length (cm)	Avg. Boulder Dimensions Width (cm)	Avg. Boulder Dimensions Height (cm)	Avg. Boulder Density (g/cm^3)	Boulder volume (cm^3)	K (m/day)
34	10.8	104.40	126.87	19.4	14.27	5.83	2.61	48675.55	12.49
33	8.2	80.00	123.14	19.49	14.31	5.91	2.75	57094.38	8.93
32	8.2	80.00	133.79	18.67	14.05	6.51	2.53	52834.95	9.98
31	7.6	80.00	124.78	19.30	14.12	6.25	2.52	49428.46	9.85
30	9.5	79.95	129.01	19.68	13.71	6.17	2.51	51316.66	9.84
29	7.0	80.00	128.94	19.53	13.96	6.18	2.53	50923.75	10.96
28	7.0	80.00	126.18	19.17	14.20	6.20	2.53	49940.06	9.40
27	9.5	80.00	127.02	19.62	14.00	6.27	2.52	50444.24	6.10
26	8.2	80.00	127.84	19.71	14.32	6.29	2.54	50315.51	7.34
25	8.2	85.45	130.68	20.45	15.19	6.44	2.54	51530.03	7.37
24	9.0	83.95	121.87	20.11	14.98	6.26	2.52	48414.69	8.06
23	7.0	84.10	129.20	21.08	15.19	6.44	2.60	49651.11	9.14
22	9.0	84.60	122.77	20.05	15.02	6.17	2.53	48531.55	8.38
21	9.5	85.20	124.48	19.77	14.72	6.02	2.55	48833.73	9.02
20	7.6	84.40	120.18	20.10	14.72	5.87	2.55	47094.90	8.48
19	9.5	85.80	120.35	19.83	14.90	6.09	2.54	47390.05	7.25
18	8.2	86.50	122.69	20.86	14.66	6.02	2.56	47850.72	9.34
17	8.2	84.50	124.81	20.42	14.72	6.40	2.57	48655.67	8.01
16	9.5	86.20	126.79	20.43	15.16	6.12	2.61	48574.06	7.67
15	9.0	85.20	136.67	20.54	15.25	6.49	2.56	53342.43	8.87
14	8.2	83.70	141.99	21.52	16.71	6.65	2.60	54575.45	11.85
13	9.0	85.95	135.80	21.49	15.82	6.22	2.55	53287.94	6.30
12	7.0	83.70	127.24	20.48	15.34	6.13	2.55	49959.10	7.98
11	10.5	84.65	131.61	20.00	14.80	5.90	2.58	51079.47	9.62
10	8.2	80.60	131.82	19.98	14.66	6.22	2.56	51534.35	7.97
9	9.2	82.05	127.86	19.62	15.40	6.46	2.55	50064.36	8.48
8	7.6	80.90	124.22	19.20	15.02	6.20	2.61	47674.65	8.57
7	9.5	86.35	127.91	19.77	15.95	6.34	2.48	51679.98	
6	7.9	80.05	127.61	19.79	15.20	6.53	2.56	49900.50	
5	7.9	80.10	123.70	20.86	15.22	6.26	2.56	48407.84	
4	9.5	81.25	116.48	20.10	14.36	6.11	2.50	46553.91	
3	9.0	82.80	117.41	20.32	14.85	6.26	2.59	45287.01	
2	5.1	69.20	110.78	18.87	14.16	5.68	2.55	43391.77	
1	3.8	80.00	—	—	First layer sand only		—	—	—

Table 14. Location of tensiometers in column.

Tensiometer No.	Depth from top of sand-boulder column (cm)
A5	1.0
A3,4	9.5
A1,2	17.8
B1,4	41.3
B1,2	51.4
C3,4	89.5
C1,2	93.2
D3,4	135.9
D1,2	144.1
E3,4	187.3
E1,2	194.9
F3,4	240.0
F1,2	248.0
F5	284.0

Table 15. Physical data and hydraulic properties of sand-boulder column.

Physical Data

Diameter	1.24 m
Height	2.83 m
Weight of boulders	4172 kg
Weight of sand	2811 kg
Density	2.04 g/cm^3
Specific gravity of boulders	2.55
Specific gravity of sand	2.66
Porosity of column	.218
Porosity of sand	.418
Void ratio of column	.28
Void ratio of sand	.72
No. of boulders	1378
Avg. size of boulders	20 x 14.8 x 6.2 cm

Hydraulic Properties

Flow rate (m/day)	Θ	h cm	Gradient	K (m/day)	D_K m^2/day	D_B m^2/day	Pore volume @ C/C₀=.5	Change in storage (cm)	Outflow-inflow (cm)
3.26	.215	0	.63	5.2					
3.26	.185	0	1.25	2.6	.82	.80	.99		
2.51	.185	-12	1.1	2.3					
1.4	.166	-34	1.0	1.4	.29	.26	.98	6.1	6.5
.32	.138	-39	1.0	.32	.10	.093	.98	7.4	7.6
.02	.087	-51	1.0	.02	.02		1.0	11.7	11.0

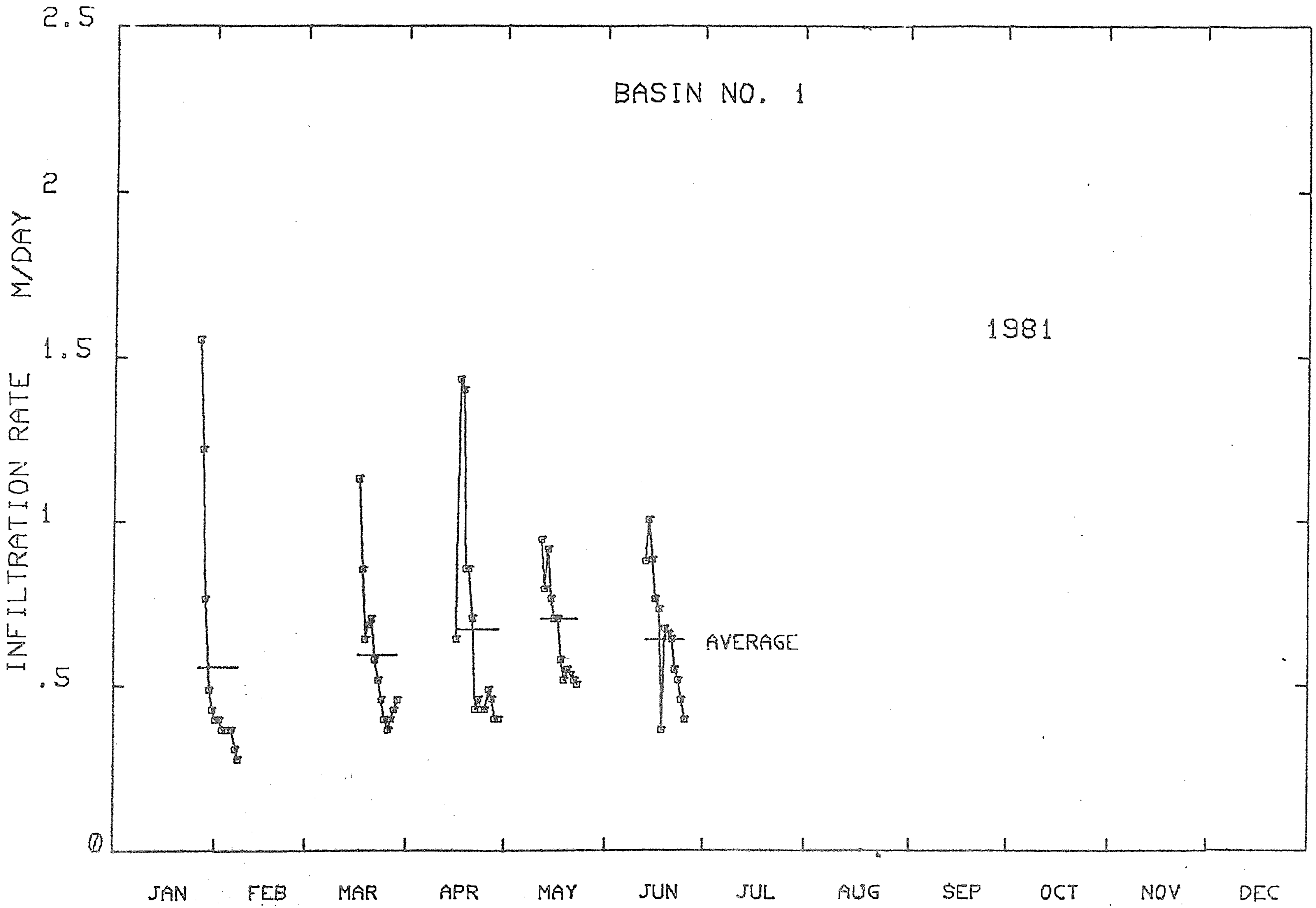


Figure 1. Infiltration rates in Basin 1.

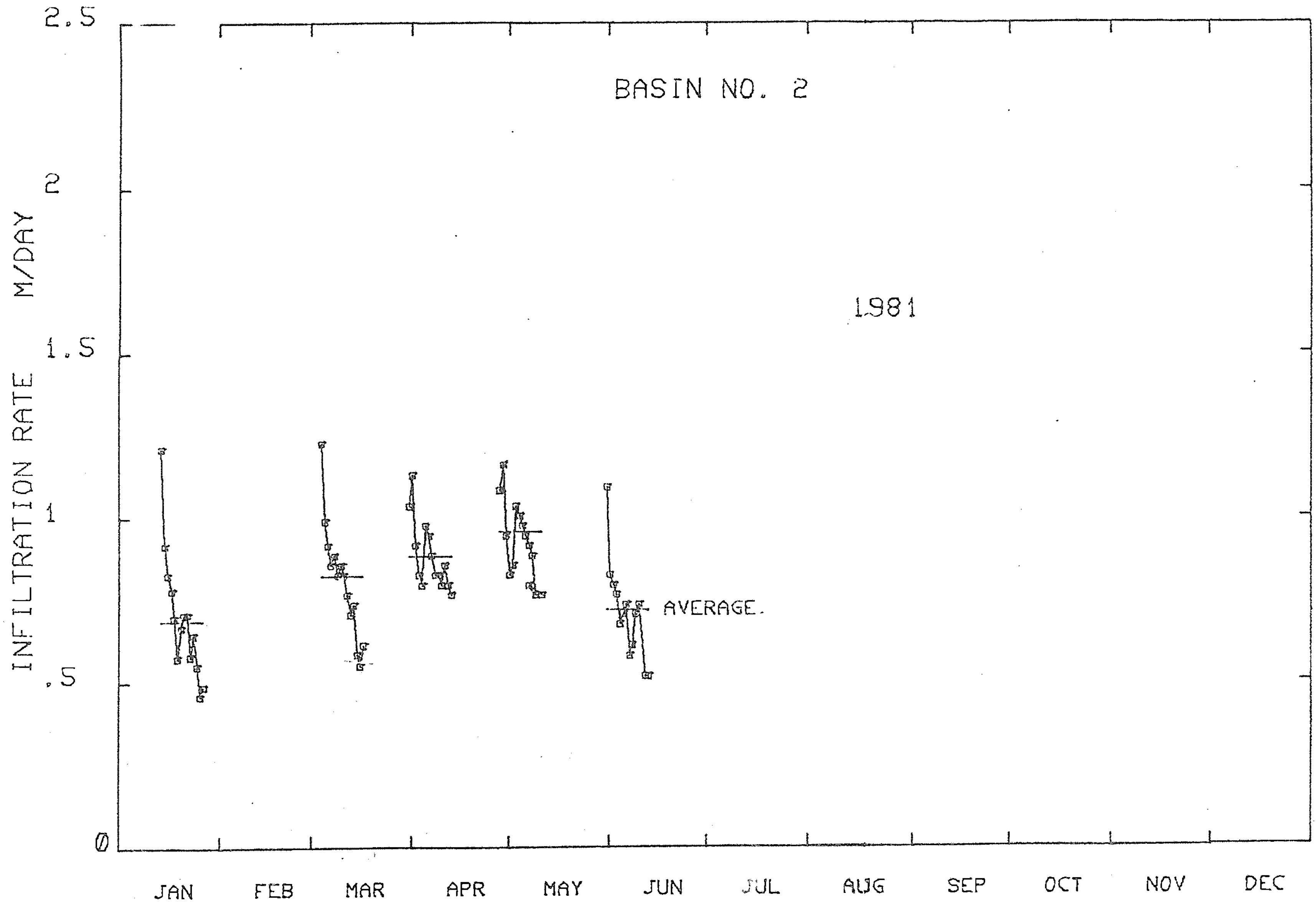
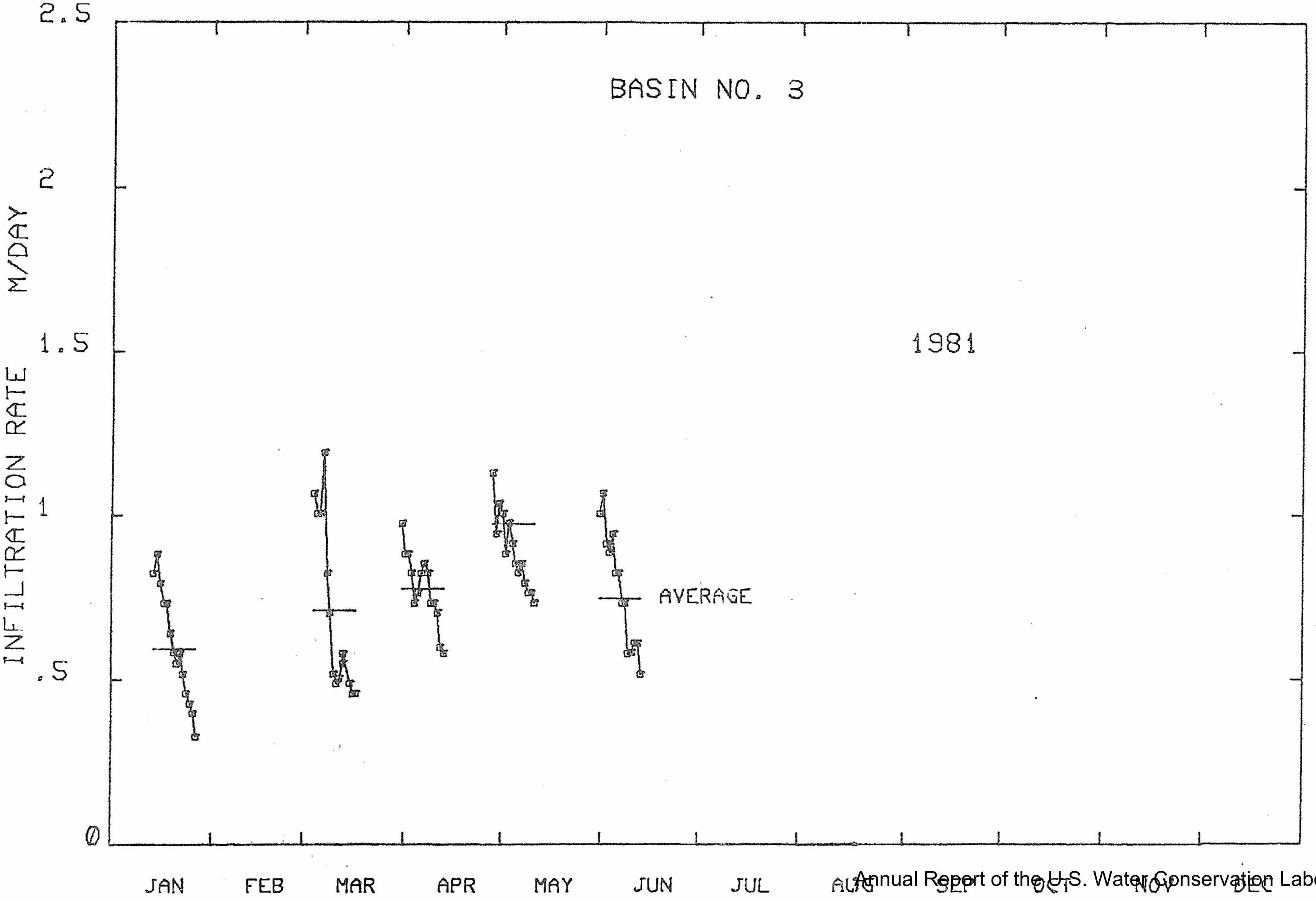


Figure 2. Infiltration rates in Basin 2.


BASIN NO. 3
1981
AVERAGE
INFILTRATION RATE M/DAY
2.5
2
1.5
1
.5
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

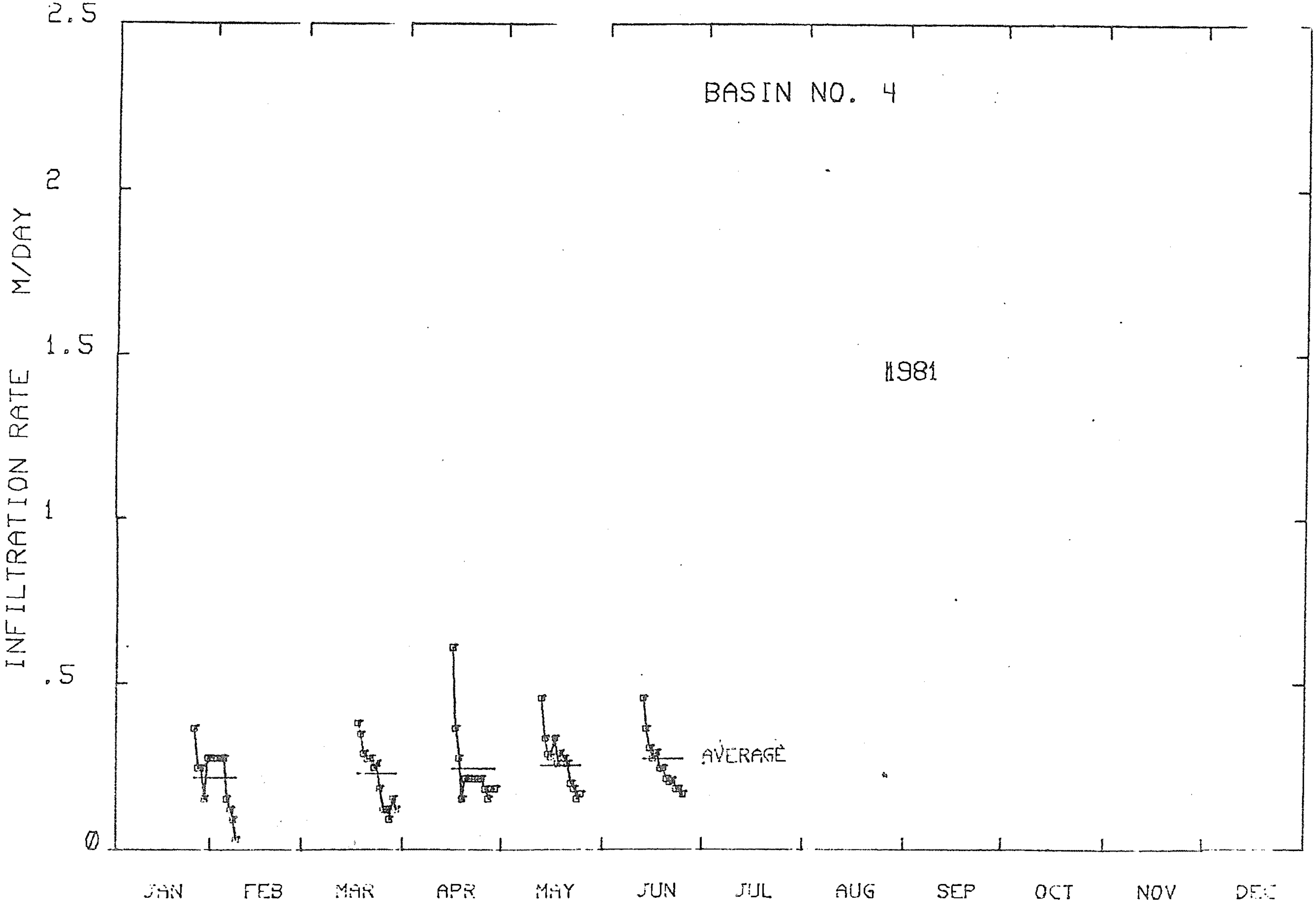
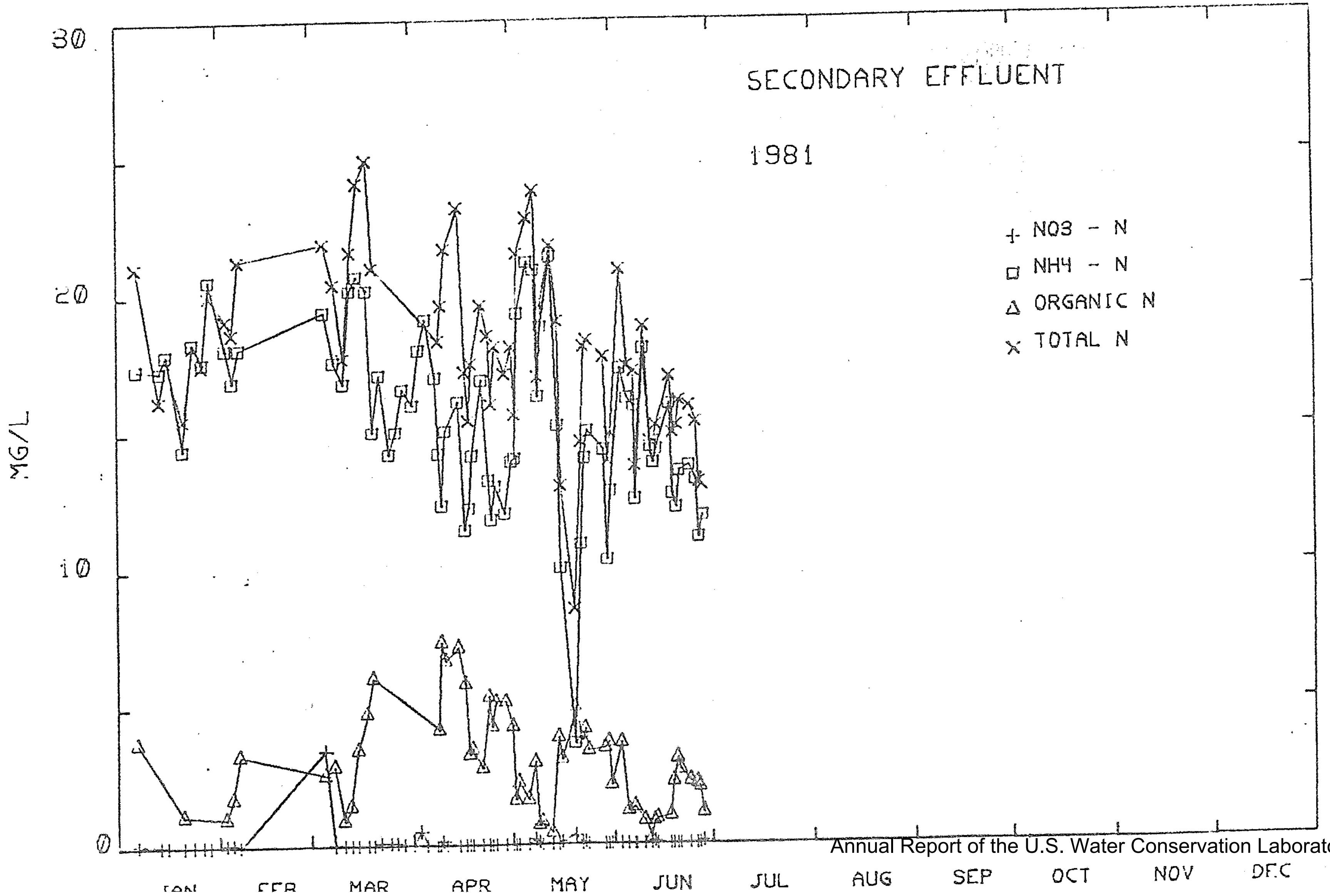


Figure 4. Infiltration rates in Basin 4.


SECONDARY EFFLUENT
1981
NO3 - N
NH4 - N
ORGANIC N
TOTAL N
MG/L
30
20
10
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

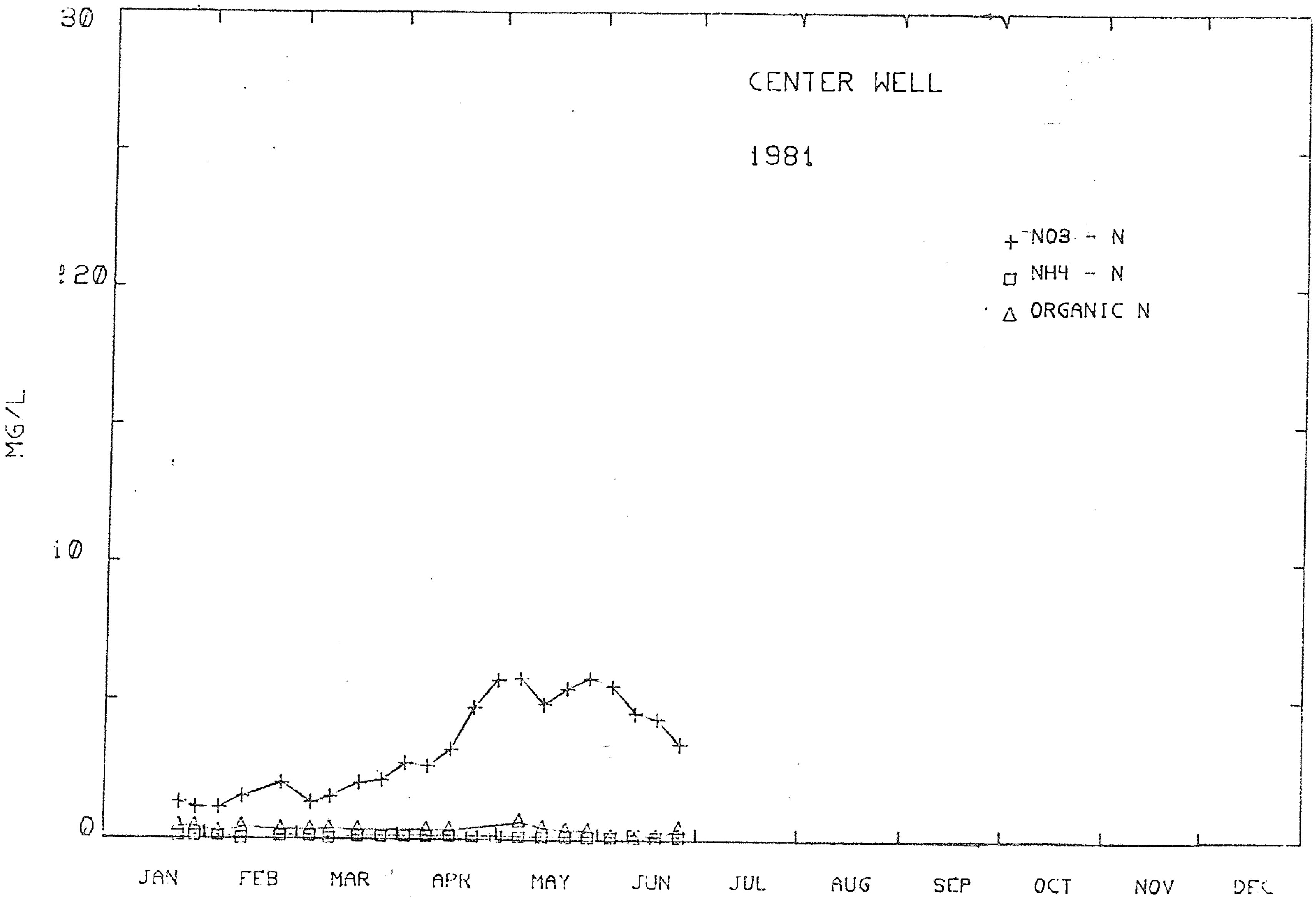


Figure 6. Nitrogen concentrations in renovated water from Center Well.

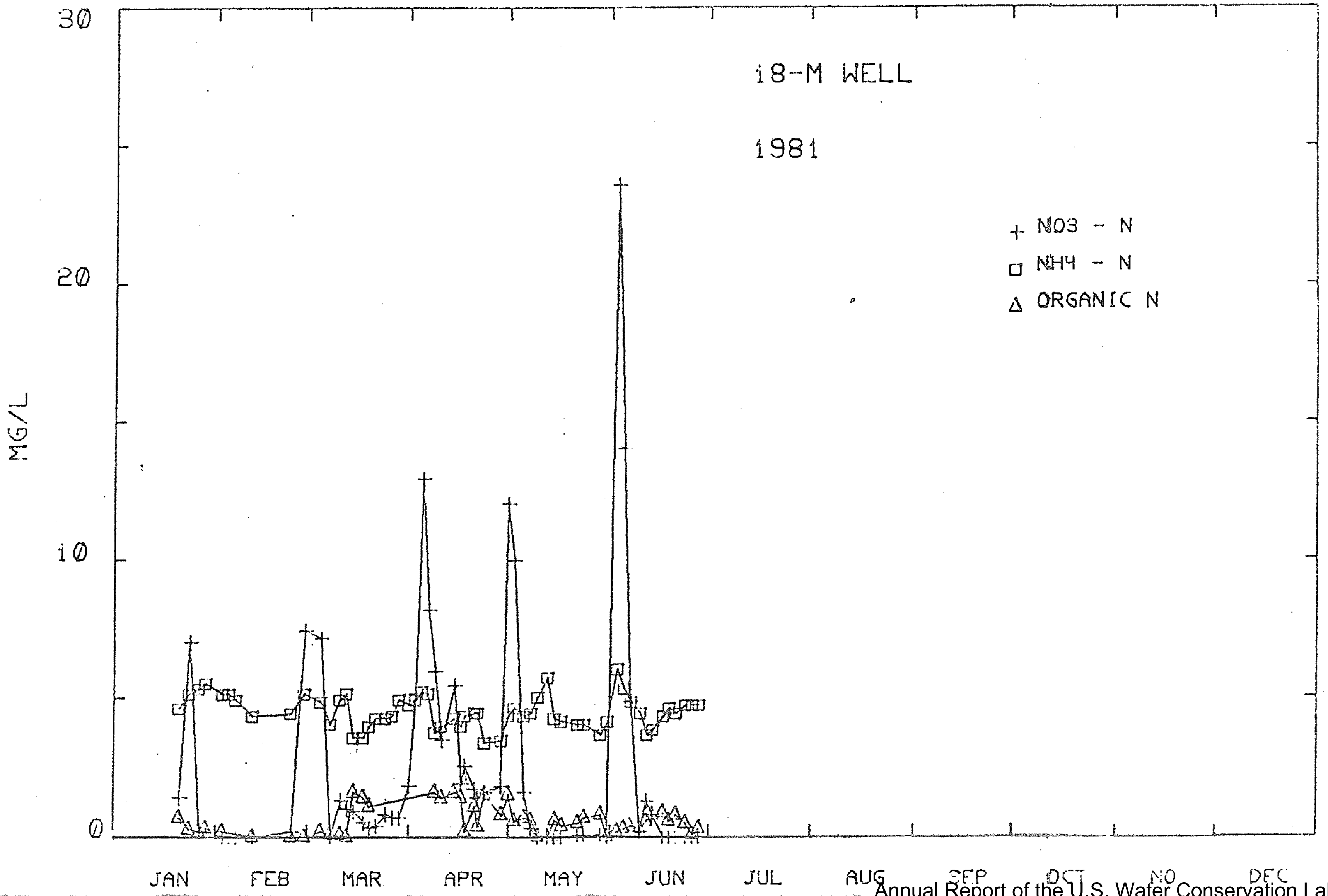


Figure 7. Nitrogen concentrations in renovated water from 18-M Well.

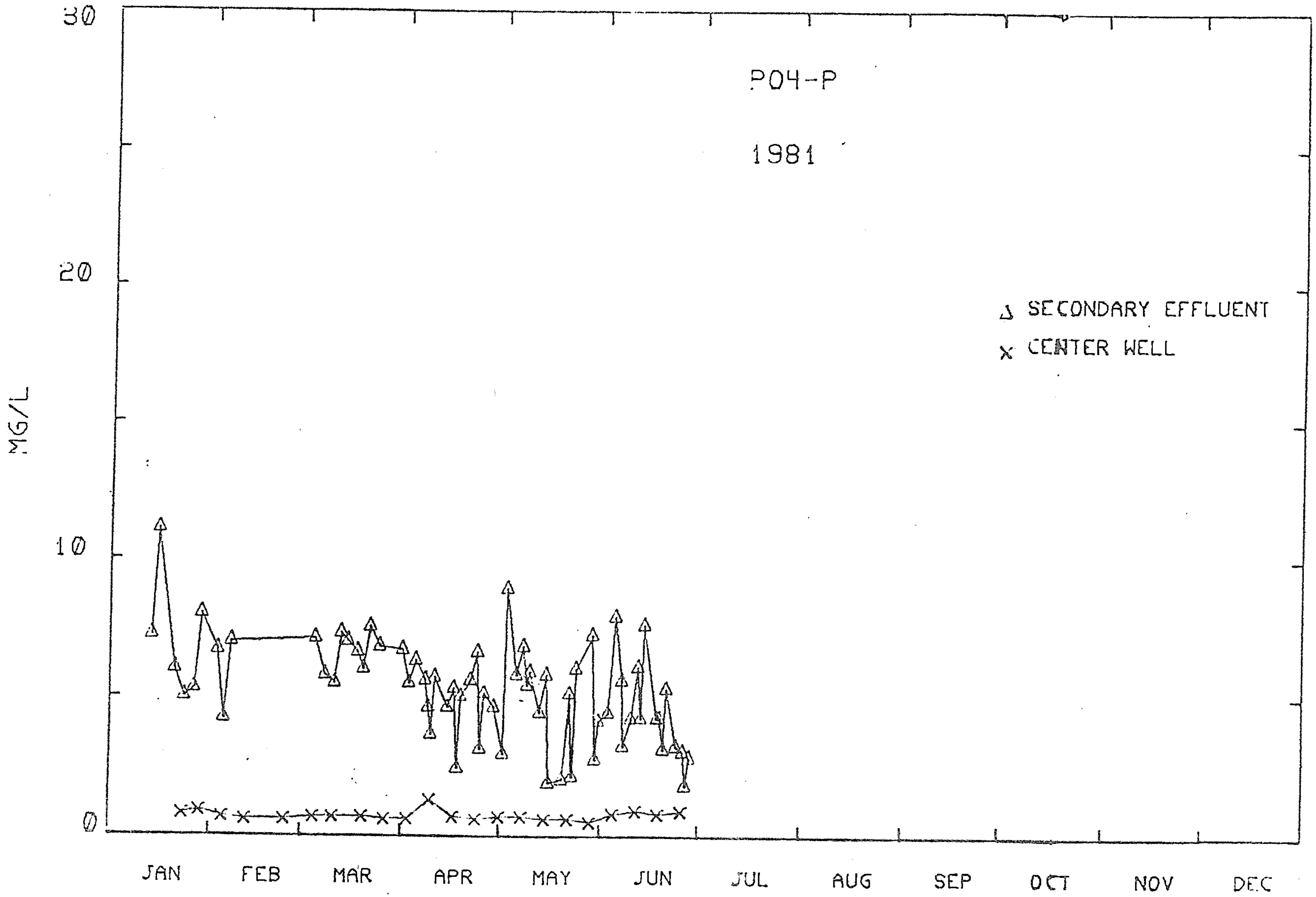


Figure 8. Phosphate-P concentrations in secondary effluent and in renovated water from Center Well.

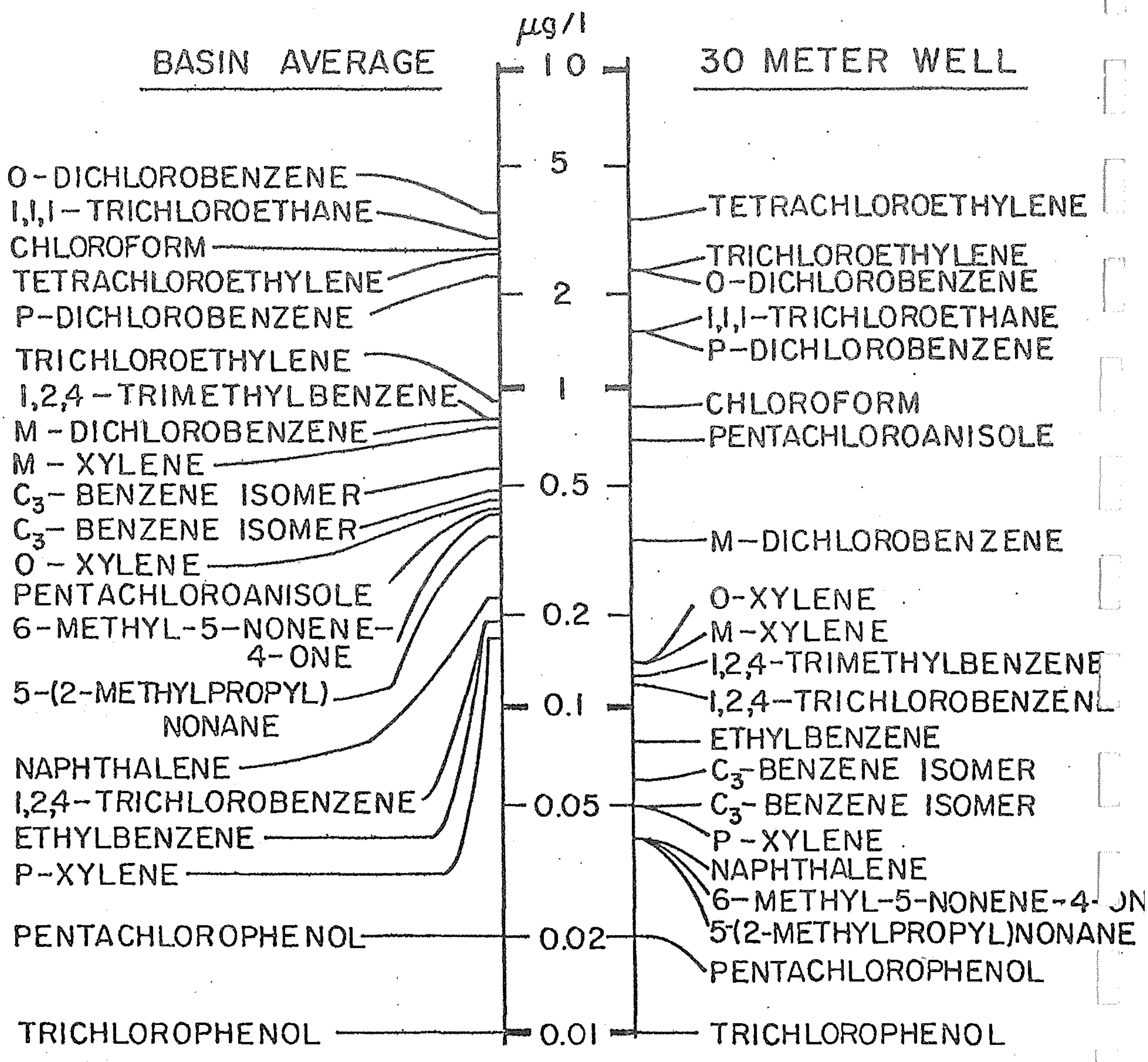


Figure 9. Concentration of organic compounds identified in basin water and renovated water from the 30-m well during period 1.

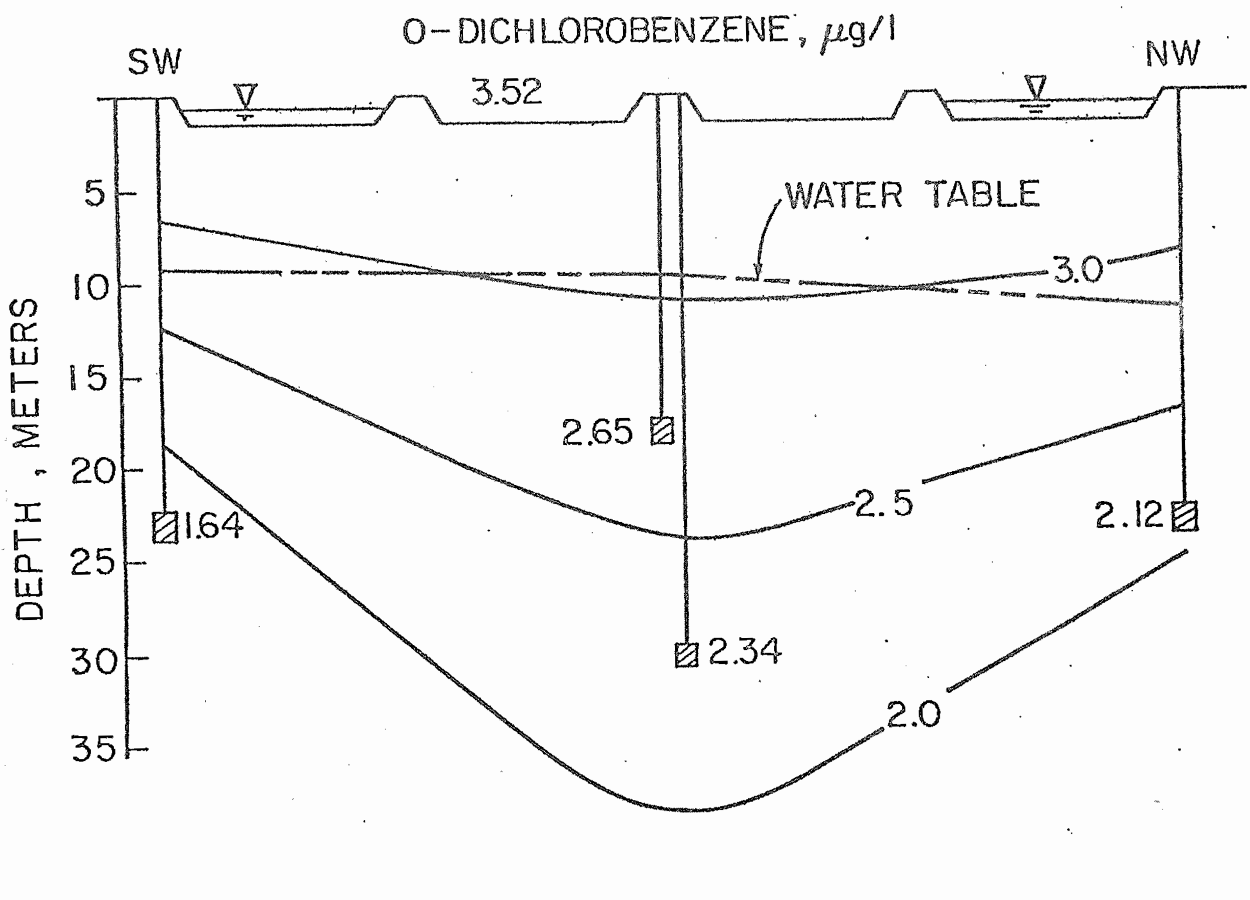


Figure 10. o-dichlorobenzene concentration contours in the underground system beneath the basins during period 1.

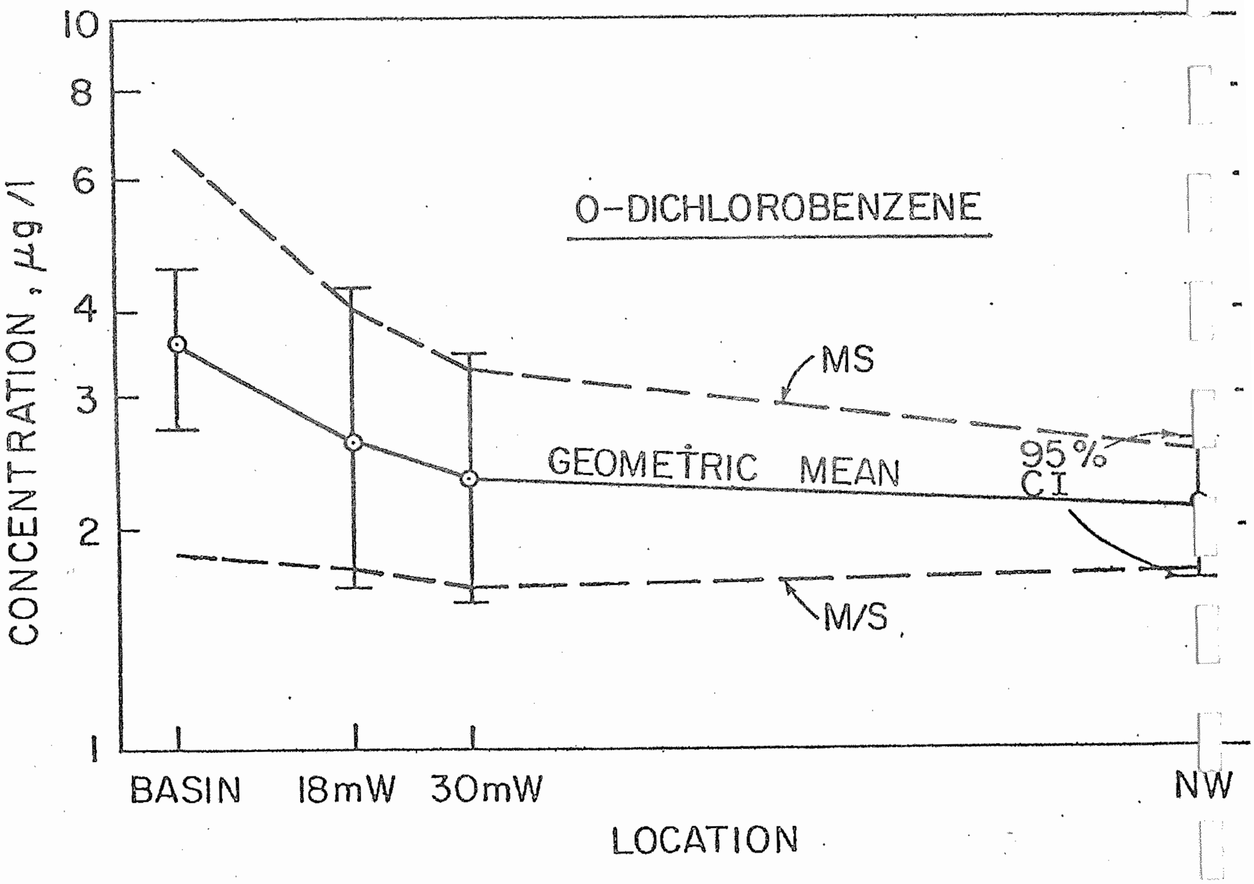


Figure 11. Geometric mean, 95% confidence interval for mean, and standard deviation (MS and M/S) for o-dichlorobenzene in effluent (basin) and renovated water from various monitoring wells in period 1.

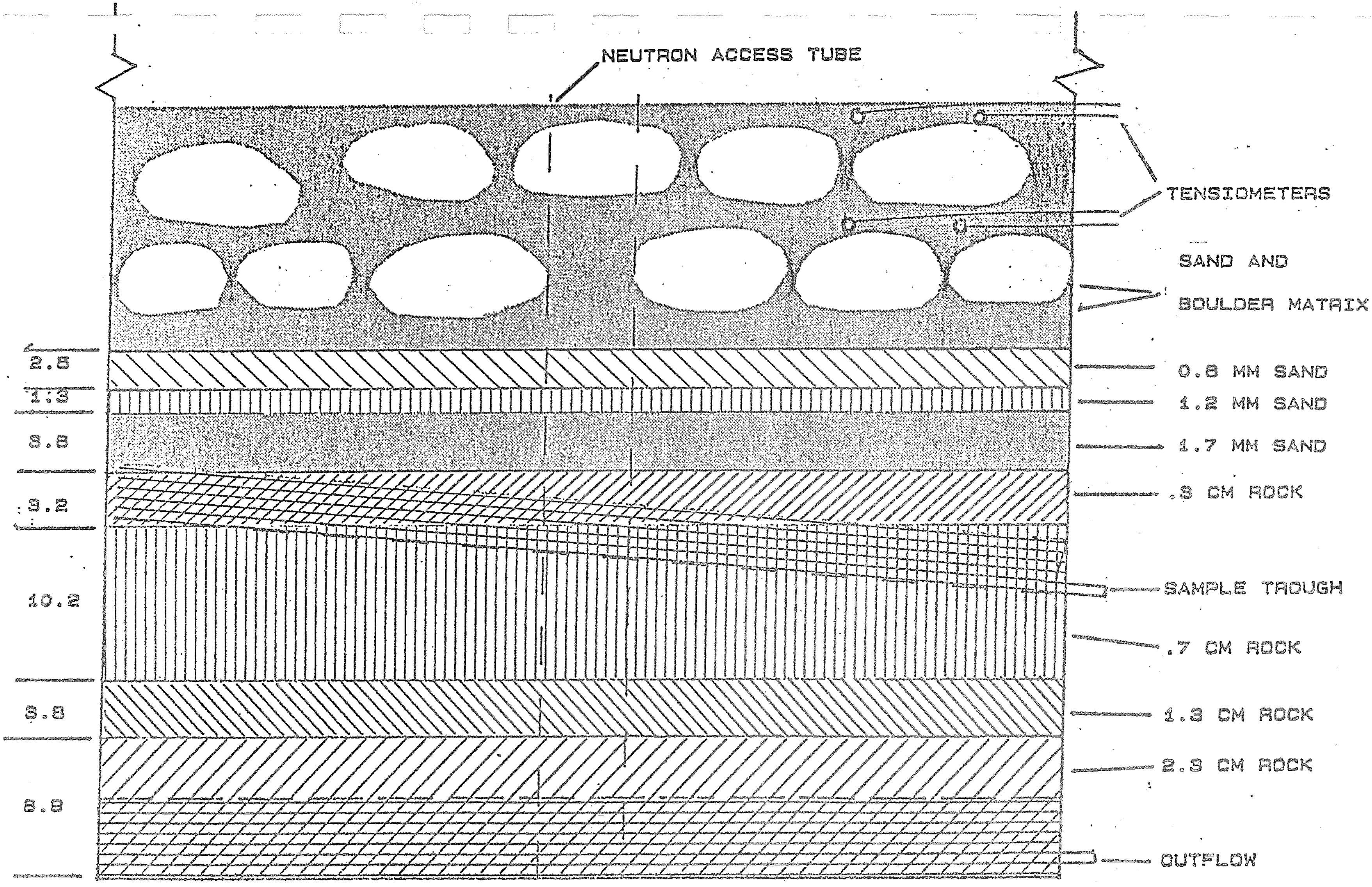


Figure 12. Sketch of lower portion of boulder-sand column showing gravel drain, tensiometer placement, and sampling trough.

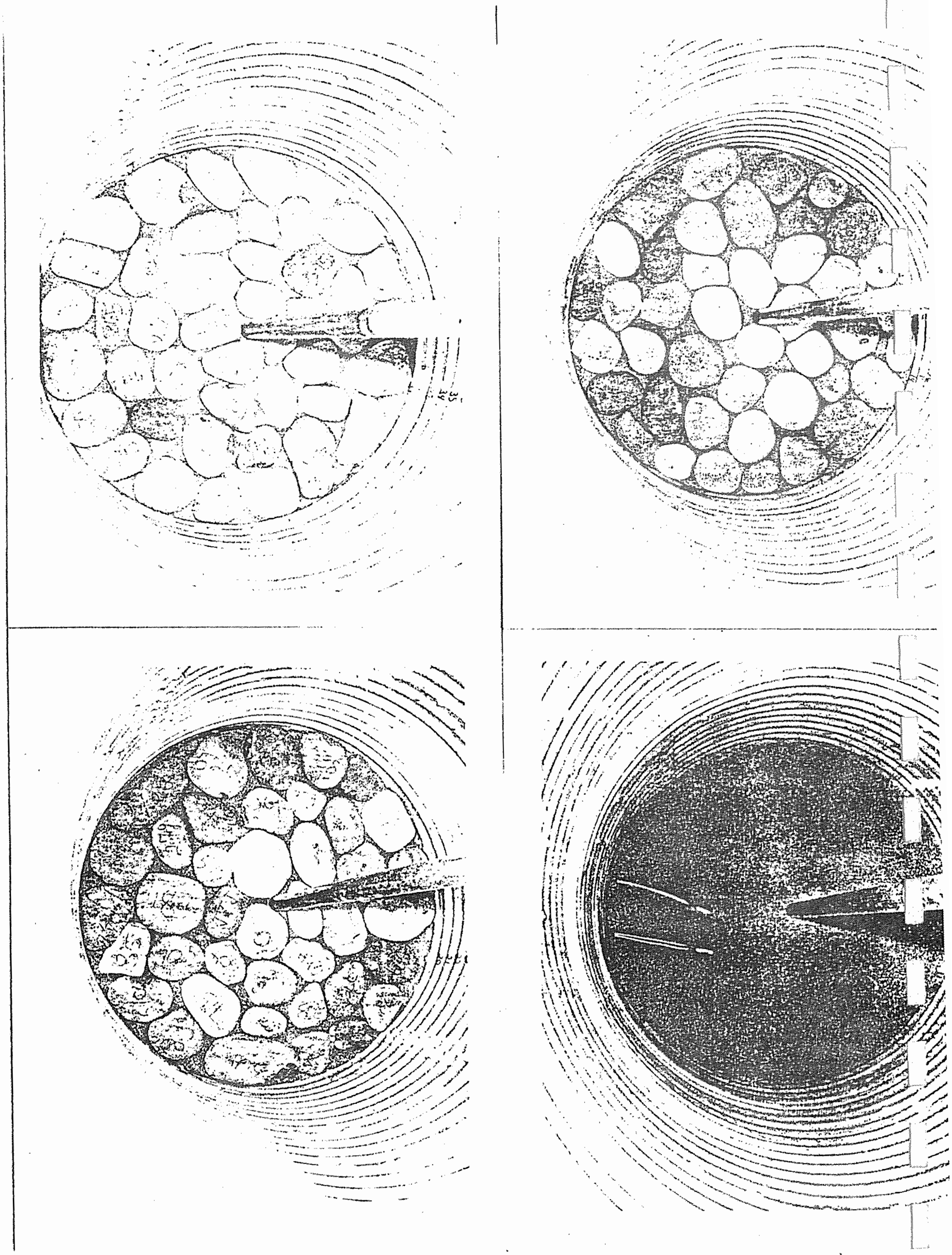


Figure 13. Photographs of different boulder layers and typical tensiometer placement.

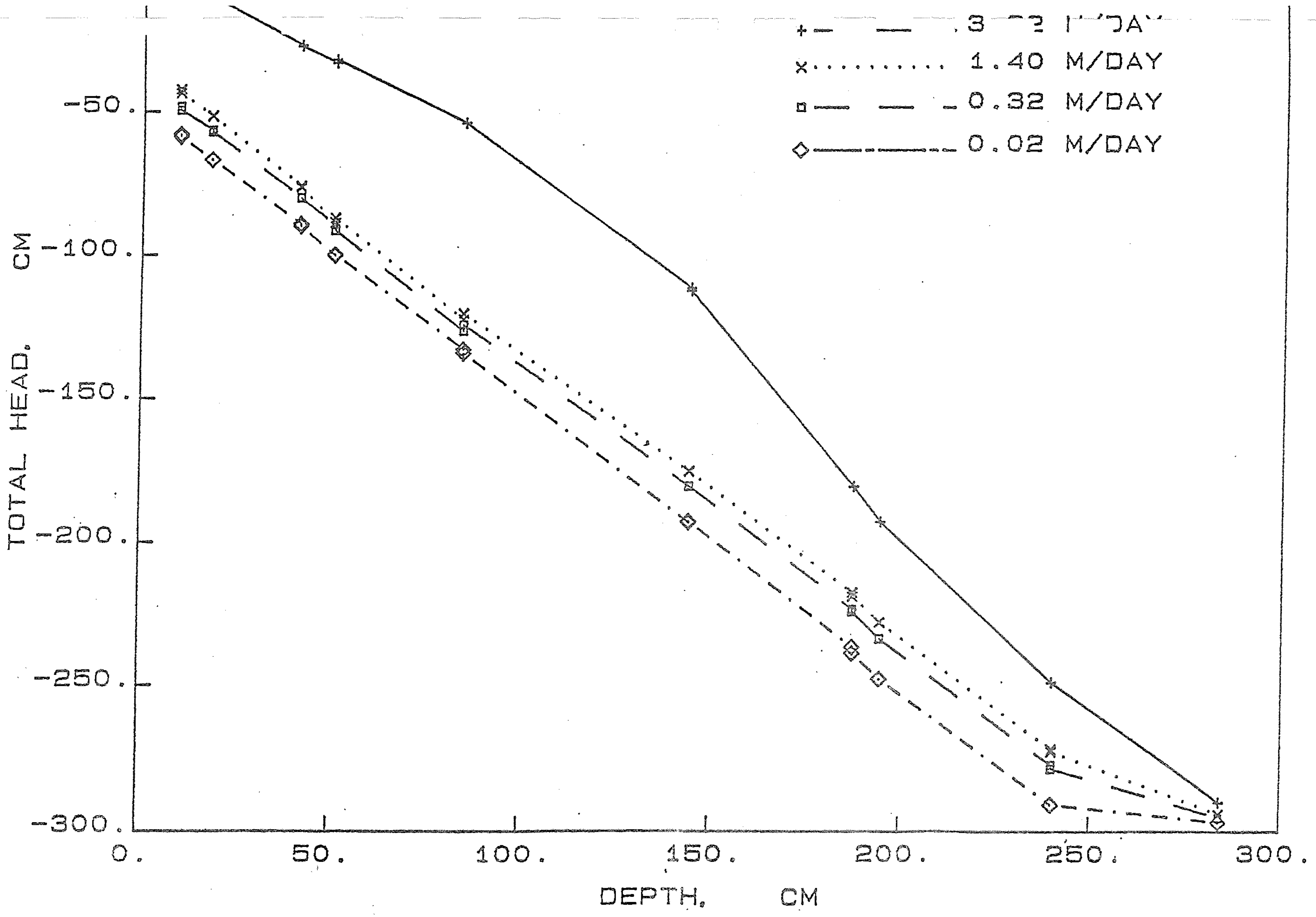
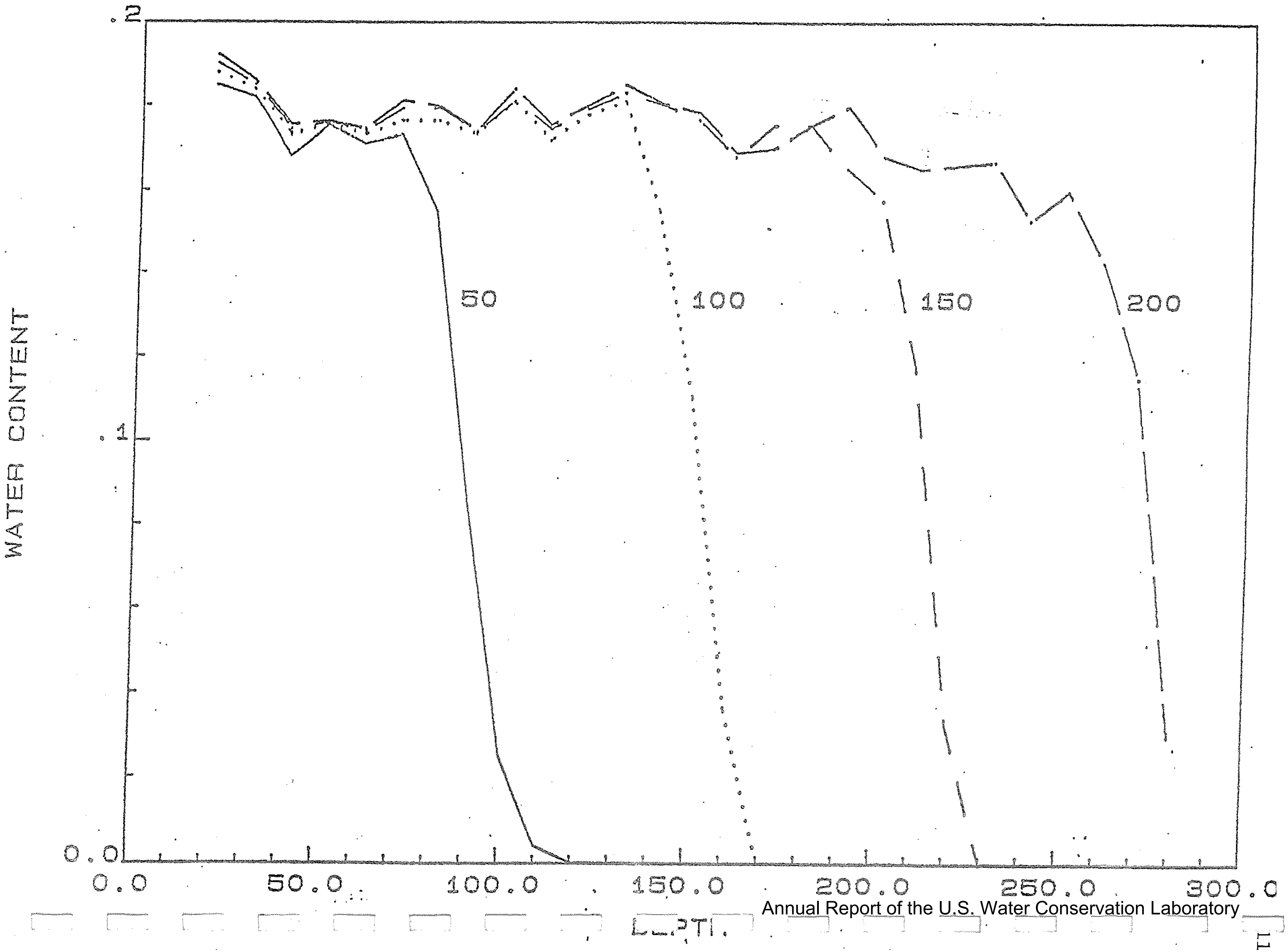


Figure 14. Total head (using top of sand-boulder column as reference level) in relation to depth in the column for different flow rates.


WATER CONTENT
.2
.1
0.0
50
100
150
200
0.0
50.0
100.0
150.0
200.0
250.0
300.0

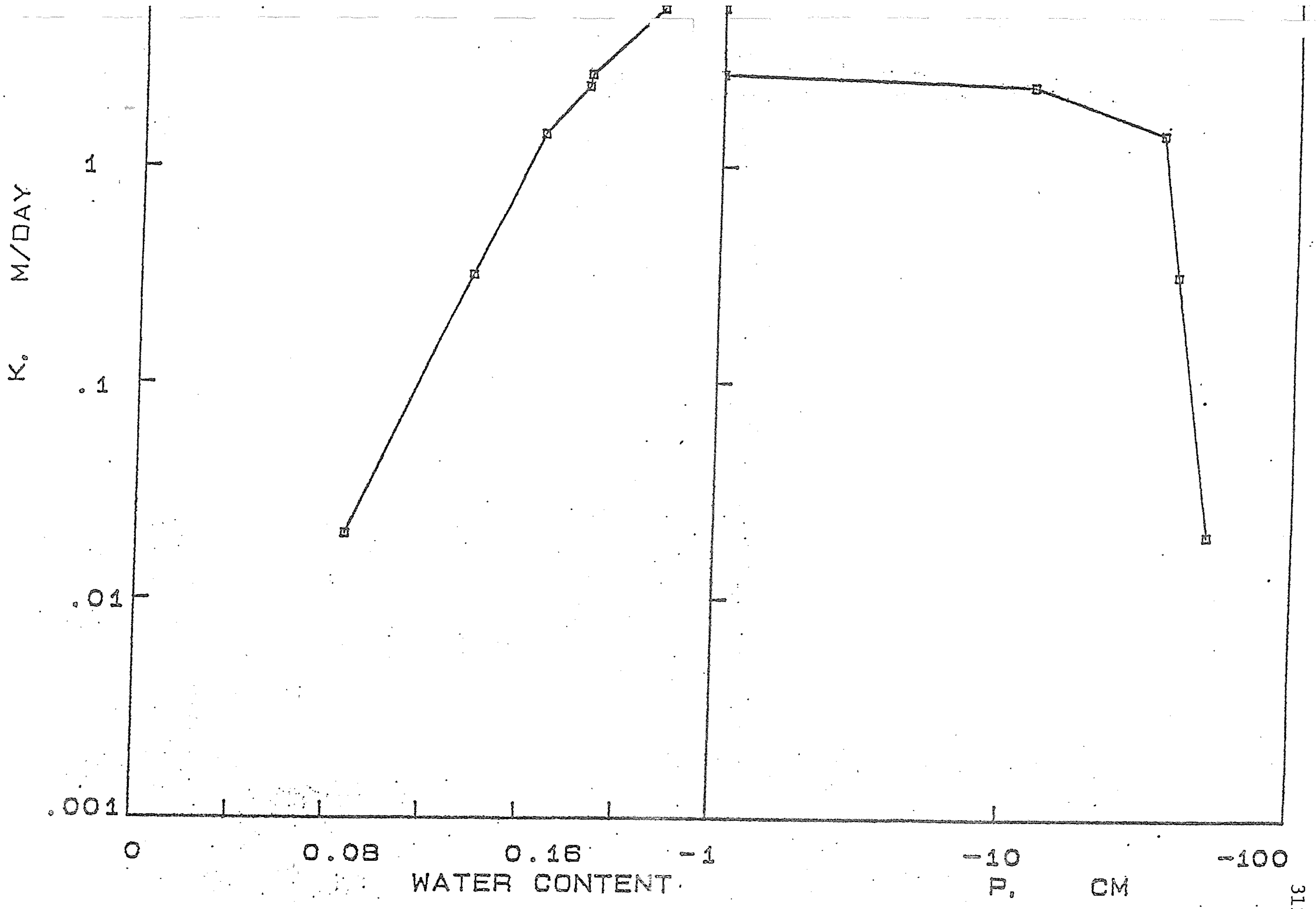
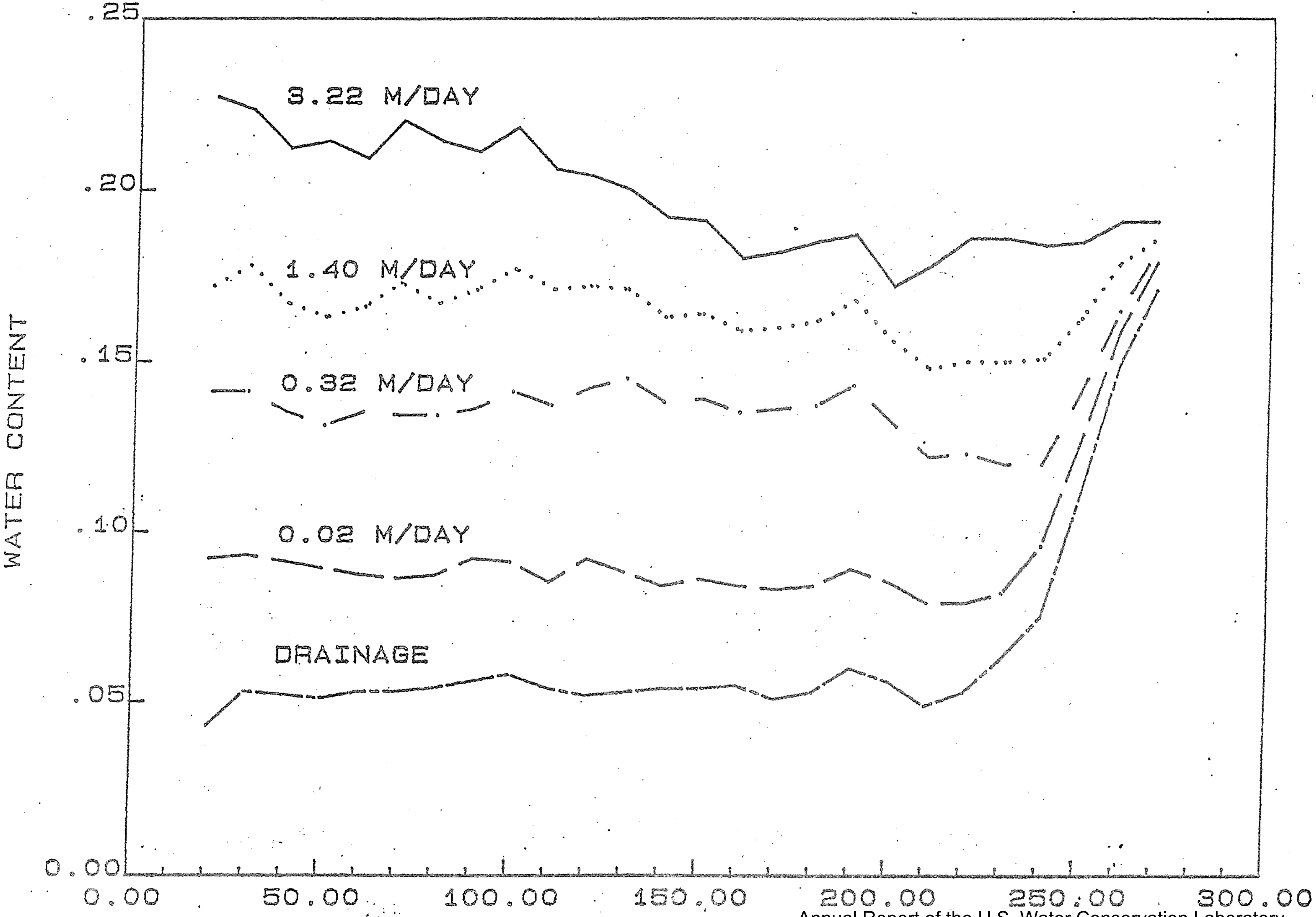


Figure 16. Water content-hydraulic conductivity and pressure head (P) - hydraulic conductivity relationships for sand-boulder column.


3.22 M/DAY
1.40 M/DAY
0.32 M/DAY
0.02 M/DAY
DRAINAGE
WATER CONTENT
.25
.20
.15
.10
.05
0.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00

DEPTH

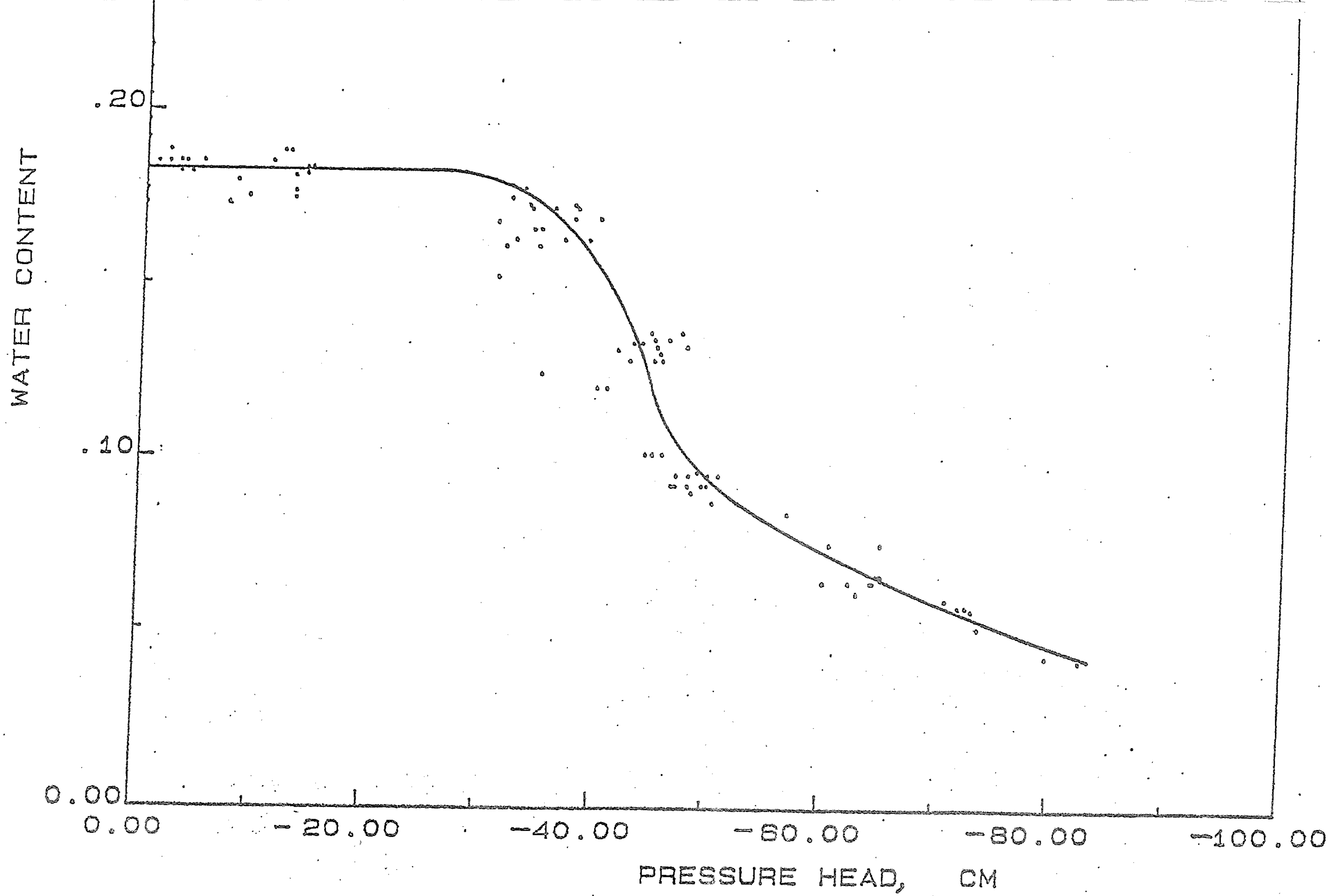


Figure 18. Water content-pressure head relationship for sand-boulder column.

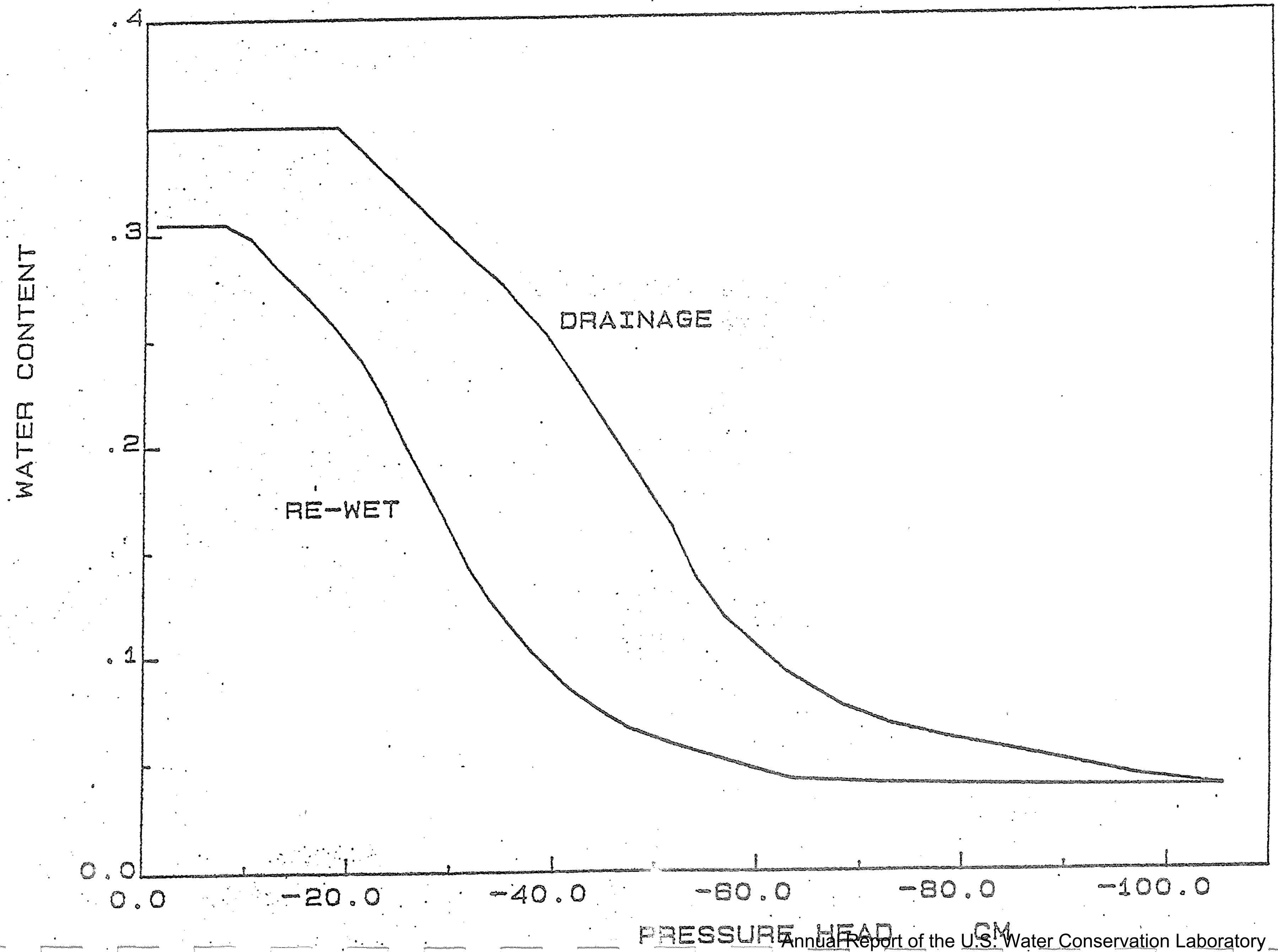


Figure 19. Water content-pressure head relationship for sand

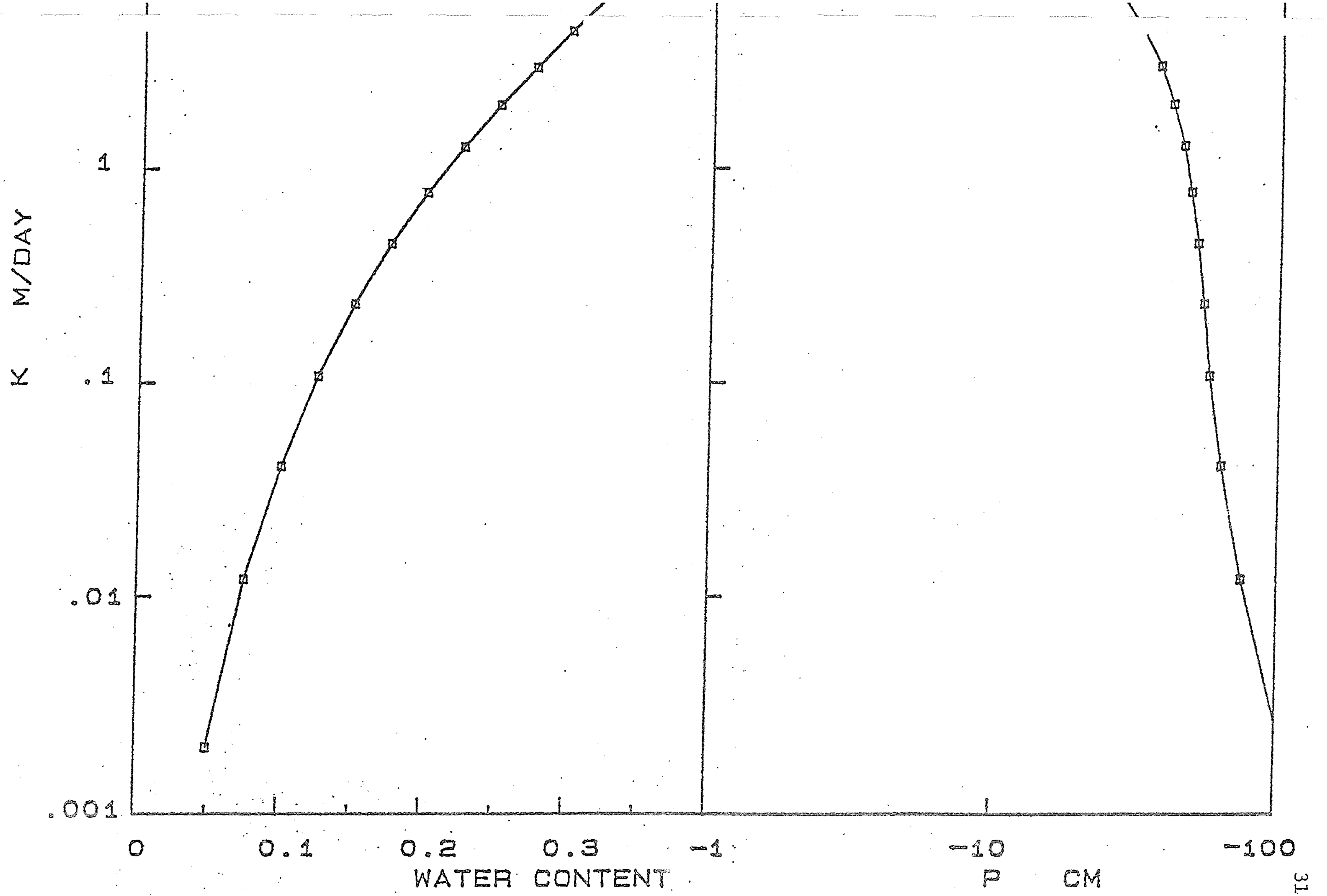


Figure 20. Water content-K and pressure head-K relationship for sand.

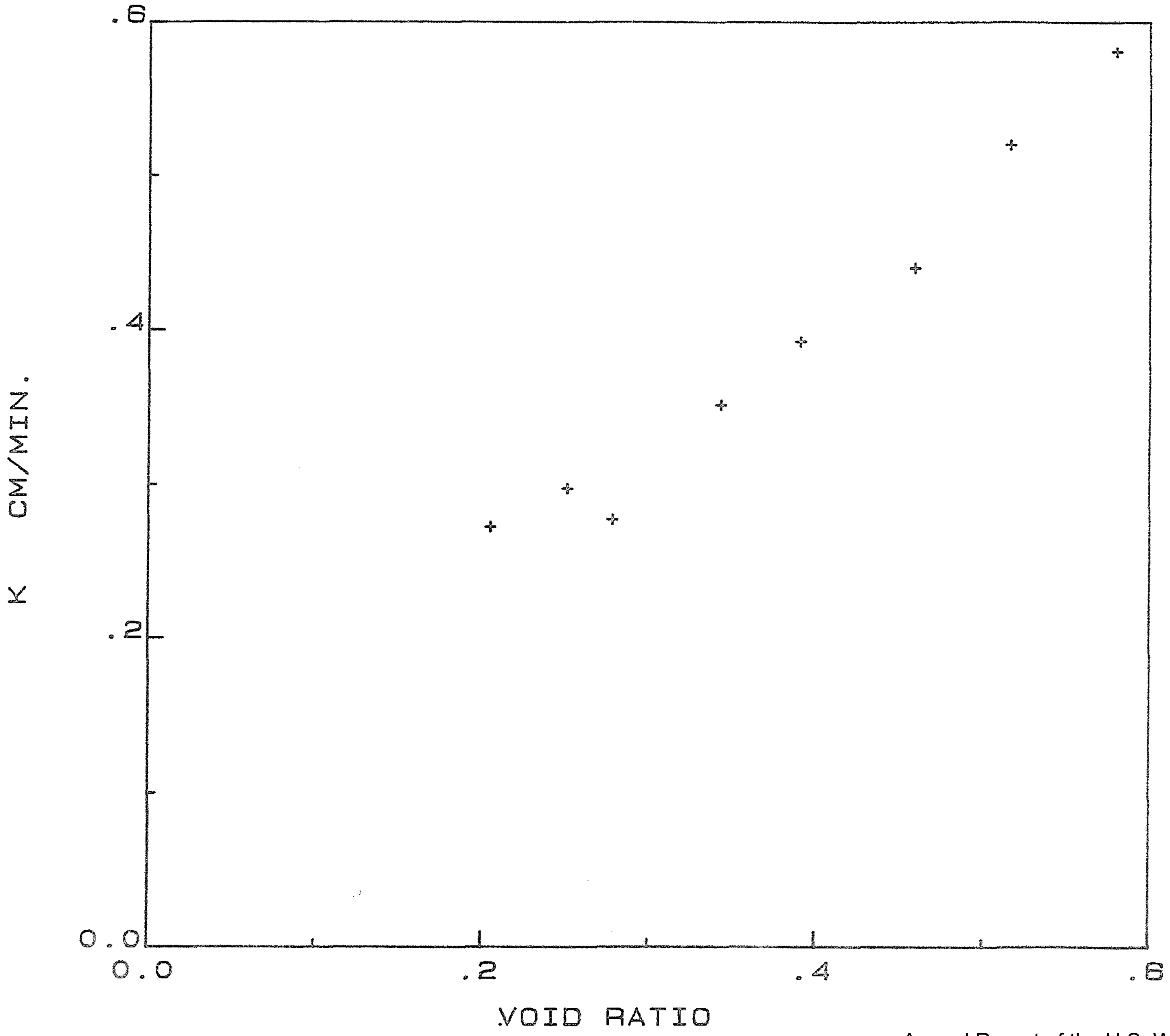


Figure 21. Void ratio-hydraulic conductivity relationship for sand-rock mixtures.

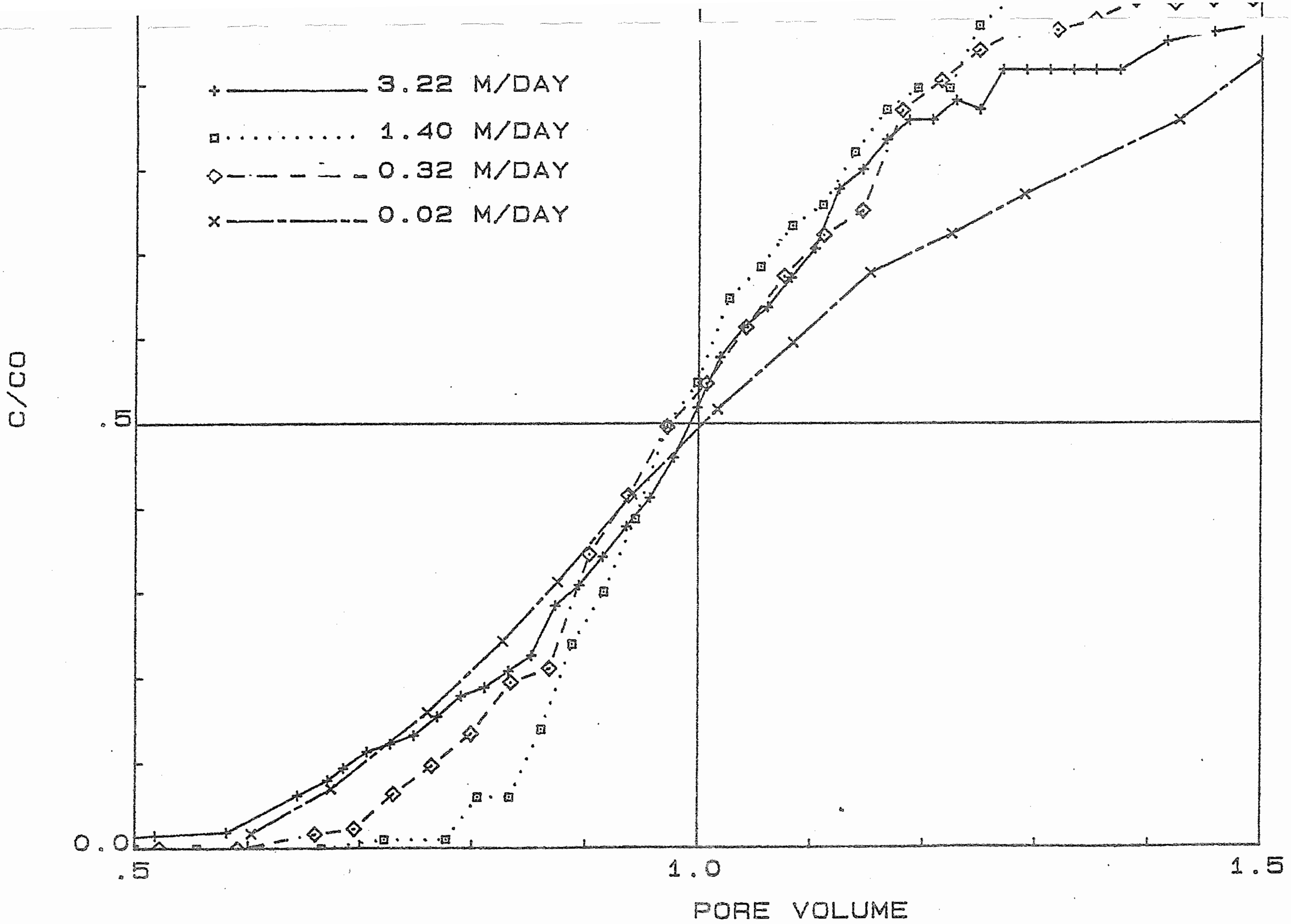


Figure 22. Breakthrough curves for salt tracer at different flow rates.

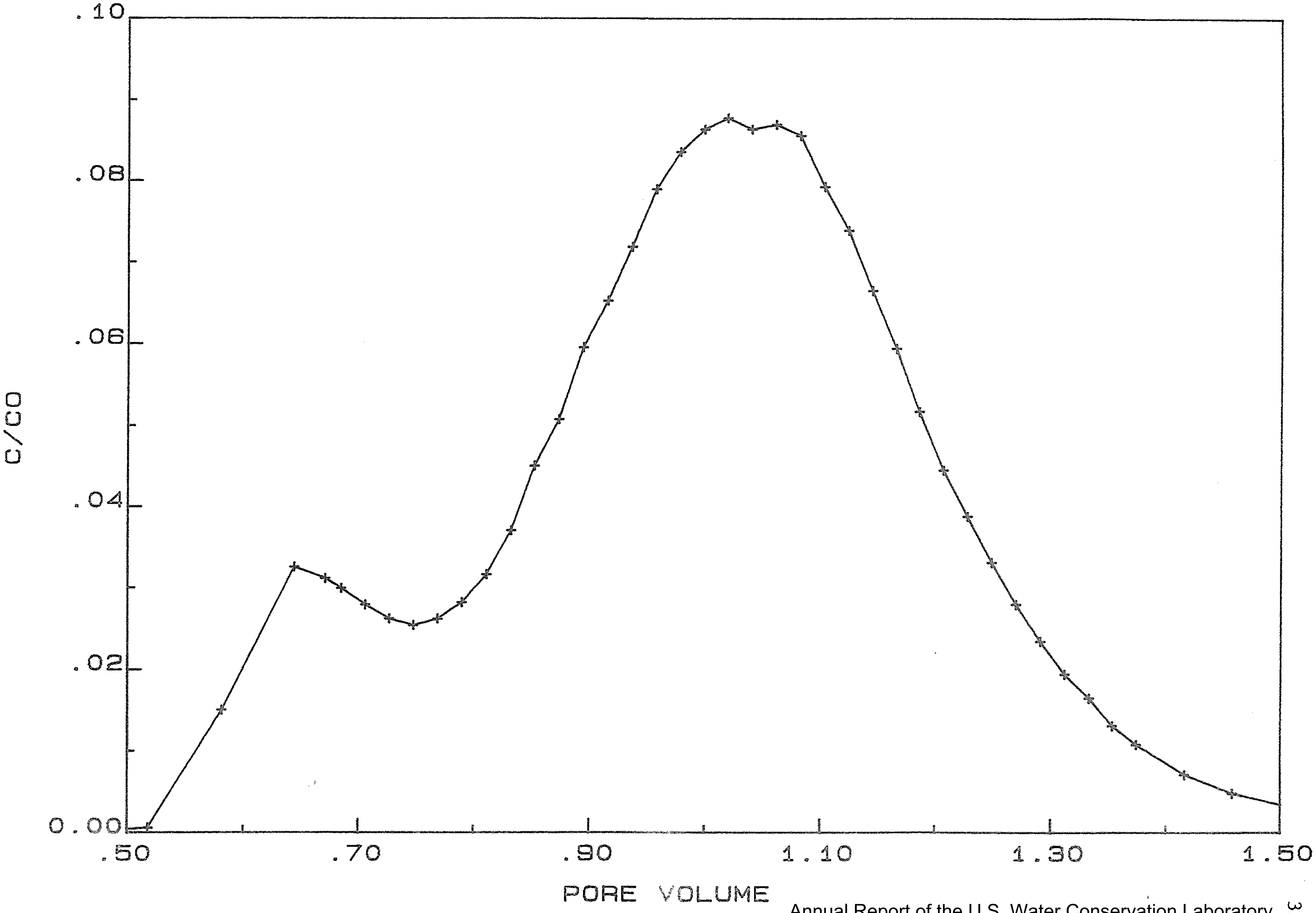


Figure 23. Breakthrough curve for slug addition of salt tracer at 3.22 m/day infiltration rate.

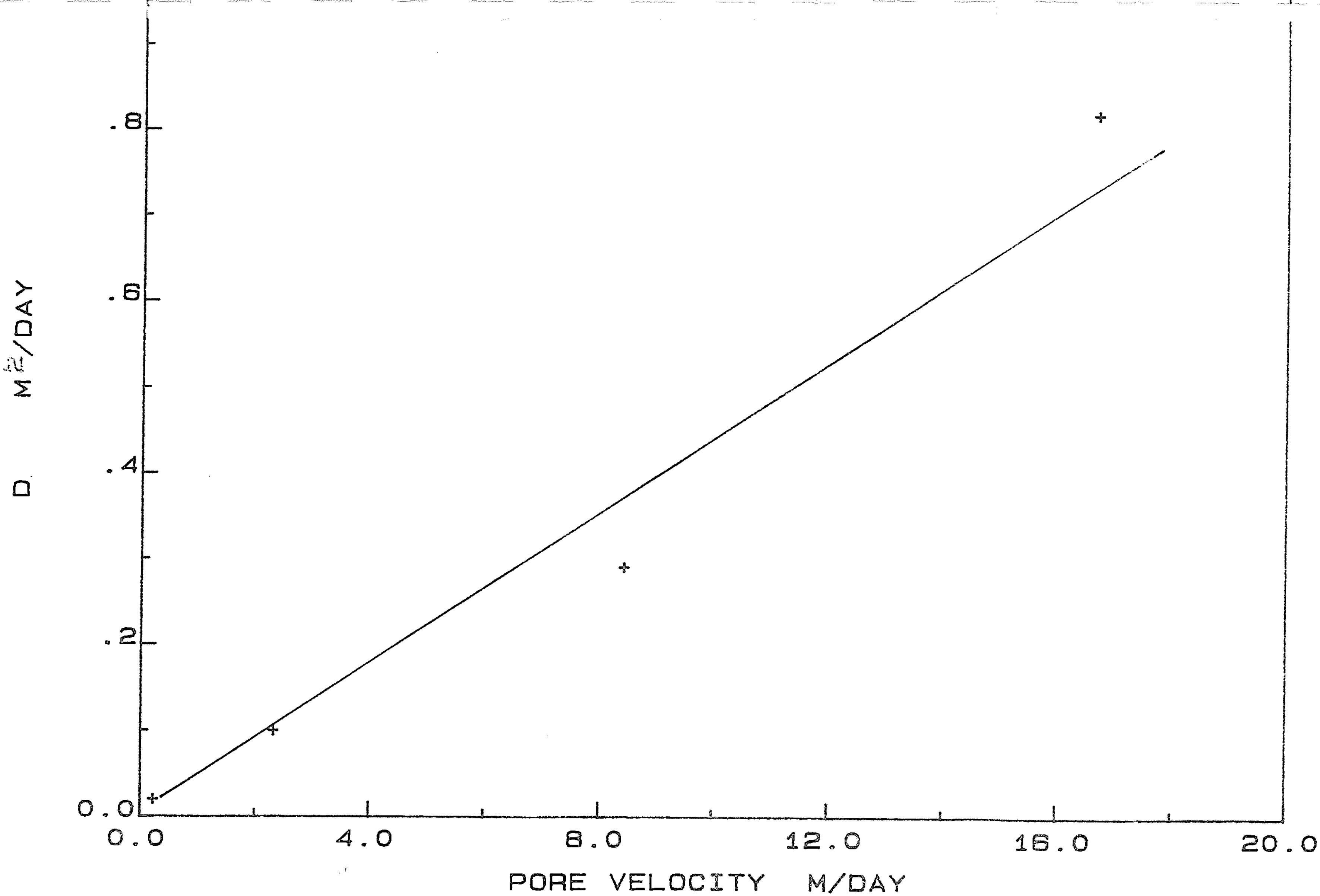


Figure 24. Dispersion coefficient-pore velocity relationship for sand-boulder column.

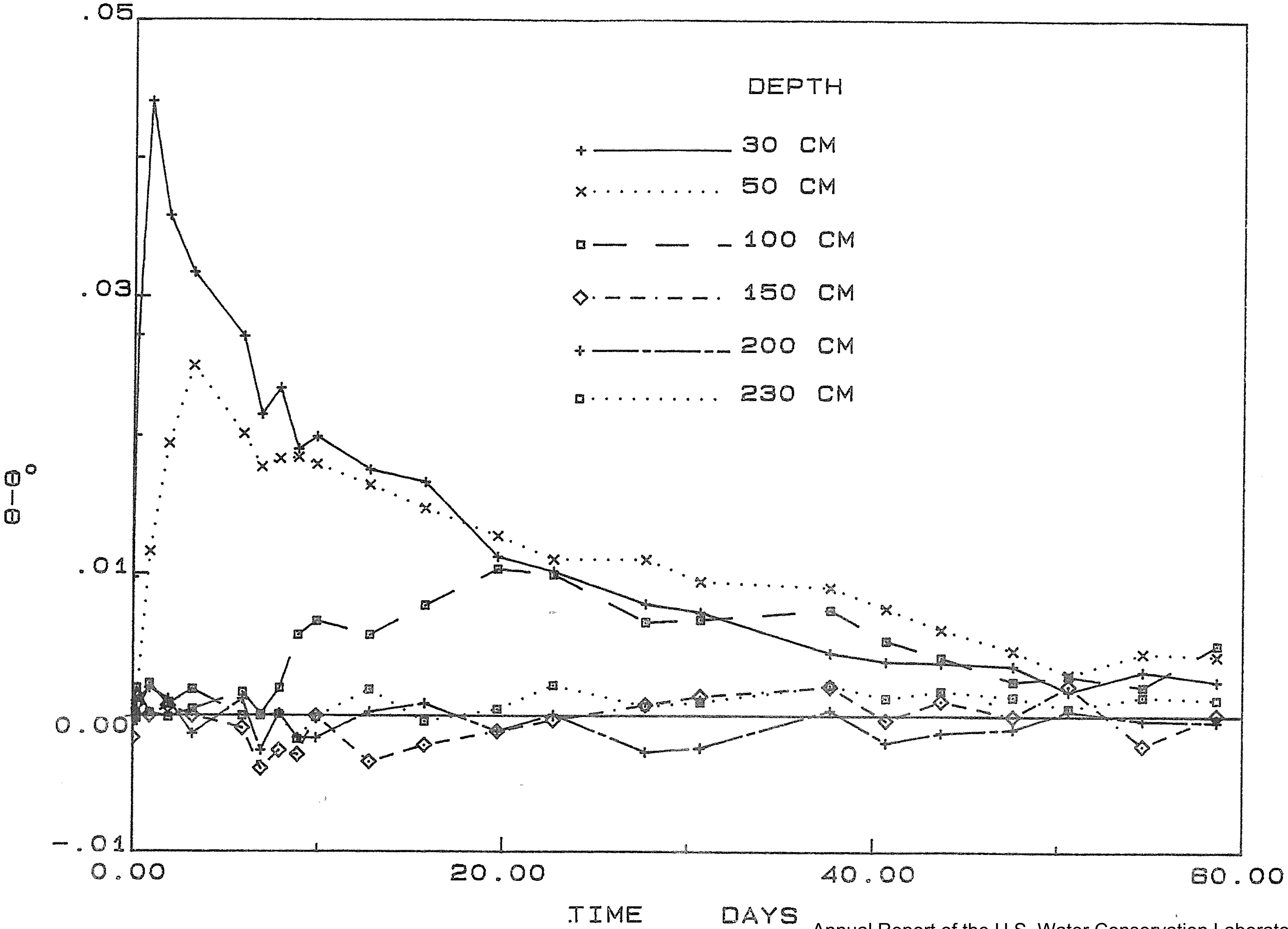


Figure 25. Water content as a function of time and depth after addition of a 2-cm pulse of

TITLE: CHEMICAL MODIFICATION OF SOILS FOR HARVESTING PRECIPITATION

RP: 20810 CRIS WORK UNIT: 5510-20810-004

LABORATORY STUDIES:

The search continued for improved water-repellent water-harvesting treatments. Past studies had shown the advantages of the wax/antistripping agent combination. Recent efforts have attempted to incorporate separate soil stabilizers to improve treatment weatherability and reduce cost by permitting lower application rates of the water repellent.

Two studies are reported here. The first used aluminum chloride as the soil stabilizer. Petri dish samples of Granite Reef soil were prepared in the usual way. The non-stabilized samples were wet with 15 mℓ water prior to packing, while the aluminum chloride samples were wet with 15 mℓ of $AlCl_3$ solution (84g/ℓ). The Al+3 added was approximately equal to the cation exchange capacity of the 150 g of Granite Reef soil in the petri dishes. Other aspects of the treatments (wax/antistrip) are summarized in Table 1. The weathering/testing sequence involved the usual freeze-thaw weathering, erosion weathering and testing, and repellency testing. This sequence was repeated until a sample failed one of the two tests or else survived 40 erosion weathering events. Erosion was done with the new wetting device described in the 1980 Annual Report.

Results (Table 1) show that the wax treatments without antistrip or stabilizer failed almost immediately (four erosion cycles maximum). Antistrip markedly improved the weatherability of the paraffin treatment. The low 0.25 kg wax per m^2 rate containing 4% antistrip weathered the full 40 erosion cycles. Obviously, according to these tests, no stabilizer could improve on this. $AlCl_3$ did partially compensate for the absence of antistrip on the paraffin treatment. Strangely, the two duplicates containing the highest paraffin/antistrip rates and Al^{+3} failed at only 22 erosion cycles.

The $AlCl_3$ treatment was more effective with the 140 slack wax than with paraffin. This twosome treatment was effective at the 0.5 kg/m^2 rate of 140. Adding antistrip made it effective at the 0.25 kg/m^2 rate.

I also tested several cement products and lime for soil stabilization (Table 2). The stabilizer-soil mixes were dry blended, placed into the dishes, wetted, and kept wet by covering with plastic for several days (5 for cement and 14 for lime). The cement coating was brushed onto the soil as a slurry and also kept wet. Waxes and antistripping agent were applied after stabilization in the usual manner. The weathering/testing procedure was the same as used for the $AlCl_3$-treated samples.

Table 2 shows that the paraffin without antistrip samples failed almost immediately, irregardless, whether they were stabilized or not. Adding antistrip to paraffin markedly improved the weatherability of the Granite Reef soil (even the low 0.25 kg/m^2 samples were satisfactory). The cement and lime stabilizers tested here did not improve the weatherability of the paraffin/antistrip treatment. Lime at the high rate decreased weatherability.

Antistrip also was needed for all the 140 slack wax treated samples, except the high (0.5 kg/m^2) wax application on the cement-coating stabilizer treatment. In general, the threesome treatments of stabilizer/140 slack wax/antistrip weathered better than those without stabilizer. Table 2 shows that practically all the threesome treated soils withstood 20 to +40 erosion cycles. Unfortunately, the duplicates of several treatments had excessive weathering variabilities. This latter problem needs further investigation.

FIELD STUDIES:

Granite Reef

Runoff efficiencies of the various plots at Granite Reef are listed in Table 3. Treatment information for each plot appears in Table 1 of the 1980 Annual Report. There were only 17 storm events in 1981 producing only 179.3 mm of precipitation. Precipitation for the six-month period 1 April to 1 October was only 51.5 mm.

The W-plots were terminated in March because the tank linings had failed (butyl torn and asphalt-fiberglass needing recoating). Table 4 summarized the runoff efficiencies of all the wax plots by years since installation. Preliminary results suggest that the paraffin treated plots will both outyield and out-survive the residual (Chevron 140 slack) wax treatments. It is too soon to assess the long-term effects of the antistripping agent and cellulose xanthate stabilizer.

On 1 June, plot T-6 was treated with a tallow derivative prepared by Warner M. Linfield of the ARS Eastern Regional Research Center. Structurally, the product is $RCONHCH_2CH_2N(CH_2CH_2NH_2)COR$, where R is the alkyl chain derived from tallow. Its melting point is 54-58°C, and has a contact angle with water of 97°. The material was dissolved in an equal weight proportion of isopropanol to facilitate application. The product had a slushy consistency.

The plot (T-6) was cleared, smoothed and compacted by several rains. The material was heated to liquify it, and was sprayed on to the plot as a hot melt using a pressure pot. The application rate of the tallow derivative was 0.4 kg/m^2.

The material did not penetrate the soil because it was already in solid form by the time it reached the soil surface. Soil temperatures, even in June, were not high enough to melt the material into the soil. The plot was covered with clear plastic sheeting in July to facilitate melting. There was some melting on the surface, but apparently penetration into the soil was minimal. The first year's runoff efficiency of only 34% was discouraging.

we attempted to treat T-8 with a 75/25 percent mixture of candelilla and 128-130 AMP white scale waxes, respectively. The plot was cleared, smoothed, rained on to compact the soil, and clipped free of weeds. The plot was stabilized on 22 July 1981 with cellulose xanthate, sprayed on as a 0.4% solution at 1.5 ℓ/m^2.

We tried, on 30 July 1981, to apply the wax mixture, which contained 3% Trymeen 6639 antistripping agent, by spraying it on as a hot melt. The intent was to apply the wax mixture at 0.3 kg/m^2. However, we could not get the temperature of the melt high enough, so had considerable trouble with plugging of lines and nozzles, and could not get uniform coverage. The runoff efficiency of T-8 has averaged only 45% since installation.

SUMMARY AND CONCLUSIONS:

Several soil stabilizers were evaluated for improving the weatherability of the wax/antistripping-agent water-harvesting treatment. Results showed that aluminum chloride salt markedly improved the weatherability for 140 slack wax and 140/antistrip treatments; had some positive effect for paraffin only treatments; but had little effect on paraffin/antistrip treatments. The latter treatment withstood maximum weathering even at the low 0.25 kg/m^2 rate provided that 4% antistripping agent was present in the wax.

Another study evaluated several cement products and lime as soil stabilizers. Results confirmed the importance of antistripping agent for the paraffin treatment. These stabilizers did not improve the weatherability of the paraffin-only or paraffin/antistrip treated soils. Some, especially lime, even made it worse.

A thin cement coating, put on top the soil as a slurry, markedly improved the weatherability of the 140 slack wax treatment. Cement, a cement dust byproduct, and lime when mixed with the soil and cured wet for several days did improve the weatherability of the 140/antistrip treatment. These soil stabilizing materials should be tested on other soil types, particularly soils higher in clay content than the Granite Reef soil.

Field evaluation of water harvesting treatments continued at the Granite Reef test site. Two attempts were made to treat plots with surplus commodity waxes; one was a tallow derivative and the other a candelilla/paraffin mixture. In both cases, the high melting point of the waxes complicated installation and prevented the waxes from penetrating the soil. Research efforts are needed to overcome both difficulties.

PERSONNEL: Dwayne H. Fink

Table 1. Weathering resistance of Granite Reef soil treated with aluminum chloride soil stabilizer/wax/antistripping agent combinations.

	No stabilizer							
	Paraffin (kg/m^2)				140 slack (kg/m^2)			
Anti-strip	0.0	0.25	0.50	1.00	0.0	0.25	0.50	1.00
%	erosion cycles							
0	0	<1	1	2	0	<1	3	3
	0	<1	<1	2	0	1	1	4
2	–	<1	+40	+40	–	1	10	10
	–	3	15	+40	–	<1	8	23
4	–	+40	+40	+40	–	<1	7	13
	–	+40	+40	+40	–	1	7	+40
	Stabilizer ($AlCl_3$) @ 1 x CEC)							
0	0	12	13	28	0	11	33	+40
	0	15	32	29	0	29	+40	+40
2	–	27	+40	+40	–	+40	+40	+40
	–	11	+40	+40	–	+40	35	29
4	–	+40	+40	22	–	+40	+40	34
	–	+40	+40	22	–	32	+40	14

Table 2. Weathering resistance of Granite Reef soil treated with stabilizer/wax/antistripping agent combinations.

	No stabilizer							
	Paraffin		140 Slack		Paraffin		140 Slack	
Wax	No A.S.	A.S.[2/]	No A.S.	A.S.	No A.S.	A.S.	No A.S.	A.S.
kg/m²	Erosion Cycles							
0.25	<1	25	1	3				
	<1	35	<1	30				
0.50	<1	+40	5	14				
	<1	+40	5	+40				
	Cement-soil mix (T/ha)							
	(2)				(4)			
0.25	1	+40	3	+40	1	+40	16	+40
	1	+40	5	27	2	27	10	+40
0.50	1	+40	7	+40	2	+40	10	25
	2	+40	7	+40	2	+40	7	+40
	Cement coating							
	(2)				(4)			
0.25	<1	18	16	7	3	15	13	+40
	1	13	20	+40	<1	17	35	+40
0.50	1	21	+40	+40	2	+40	+40	+40
	<1	17	+40	+40	2	18	+40	+40
	Cement dust-soil mix							
	(2)				(4)			
0.25	<1	28	2	+40	<1	30	4	+40
	<1	15	1	3	<1	+40	7	+40
0.50	2	+40	2	*	1	+40	7	29
	<1	+40	3	-40	1	+40	6	+40
	Lime-soil mix							
	(2)				(4)			
0.25	1	37	10	+40	1	5	10	35
	1	14	3	33	1	5	17	+40
0.50	2	+40	9	+40	2	23	8	+40
	1	+40	7	+40	2	17	3	+40

* Sample broken during testing.

1/ "No stabilizer" treatment actually had zero tons per hectare.

2/ A.S. stands for 4% trymeen 6639 antistripping agent in wax.

Table 3. Rainfall-runoff from water harvesting plots at Granite Reef in 1981.

Date	Precip.	L-1	L-2	L-3	L-4	L-5	L-6	L-7	R-1	R-2	R-3	R-4	A-1	A-2	A-3	A-4	A-5
1981	mm	%															
11-12 Jan	10.7	112.5	0	14.6	81.3	UN	109.4	71.0	0	124.9	0	8.3	113.7	21.5	0	9.8	95.1
09 Feb	27.2	95.7	0	29.6	89.2	UN	101.0	67.1	1.3	102.1	0	11.6	99.5	26.2	0	13.7	+
26 Feb	3.3	87.6	0	0	81.5	UN	88.6	32.7	0	89.1	0	0	83.3	8.6	0	0	94.2
01-03 Mar	17.5	90.6	0	25.5	94.6	UN	97.8	60.4	3.1	100.2	0.8	8.6	98.0	36.4	0	13.6	92.6
04-05	3.3	78.0	0	2.0	63.3	UN	84.5	36.2	0	74.9	0	3.6	91.8	0	0	12.1	69.8
05-06	9.6	85.8	?	36.1	95.3	UN	99.6	58.5	9.8	97.0	10.3	24.4	91.0	37.4	14.9	35.3	89.1
02 Apr	7.6	?	0	4.8	82.2	UN	115.3	63.4	0	123.4	0	5.7	122.7	29.5	0	8.3	118.7
27-28 May	2.0	72.0	0	0	56.5	UN	83.5	9.5	0	M	0	0	76.9	0	0	0	86.5
11 Jul	3.3	68.2	0	0	70.9	UN	74.8	12.7	0	59.2	0	0	77.8	0	0	0	M
15-16	16.5	?	0	24.7	94.5	UN	99.8	54.8	12.0	96.0	M	12.6	89.7	35.4	7.5	15.8	M
21	1.5	NP															
29	3.8	NP															
31	4.5	79.8	0	12.2	81.6	UN	84.5	59.4	25.5	81.5	30.7	25.8	78.6	25.0	8.7	30.4	81.8
04 Sep	3.2	NP															
24	9.1	NP															
02 Oct	24.4	88.2	36.7	M	92.6	UN	M	M	40.7	94.8	52.1	55.0	M	56.1	40.9	57.7	89.4
30 Nov	31.8	83.5	0.5	24.1	90.4	UN	84.0	53.8	8.7	91.9	8.9	18.0	91.4	33.6	9.1	23.4	M
Totals**	179.3	91.1	6.0	24.9	89.0	UN	95.7	57.2	11.0	97.9	12.5	19.1	95.9	32.9	9.9	23.0	92.8

Notation: M = Mechanical malfunction; UN = Untreated; NP = Not pumped (precipitation data from tipping-bucket raingage);
? = Questionable data.
* = Initiation of new treatments, maintenance of catchment, or termination.
** = Percentage totals are based on measured data only; i.e., no estimates.
+ = Accumulated precipitation events.

Table 3. Rainfall-runoff from water harvesting plots at Granite Reef in 1981 (continued).

Date	Precip.	W-1	W-2	W-3	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9	T-10	T-11	T-12	T-13	T-14	T-15
1981	mm	%																	
11-12 Jan	10.7	7.0	7.8	12.9	108.4	70.1	74.7	64.5	92.5	UN	86.9	UN	104.7	21.5	104.7	57.0	82.2	1.1	100.9
9 Feb	27.2	7.1	8.2	13.9	108.1	79.0	80.9	68.0	100.0	UN	93.0	UN	98.5	28.7	106.6	66.9	86.4	7.7	105.5
26 Feb	3.3	0	0	0	63.6	60.6	45.4	39.4	75.8	UN	75.8	UN	115.2	0	100.0	42.4	72.7	0	106.1
01-03 Mar	17.5	∔	∔	∔	110.1	62.3	79.4	73.1	98.2	UN	92.6	UN	106.3	32.6	103.4	70.8	81.1	9.7	103.4
04-05	3.3	7.9	9.9	13.3	93.8	45.4	36.3	51.5	75.7	UN	57.5	UN	81.8	9.1	69.6	60.6	66.6	0	75.7
05-06	9.6	8.0	10.2	9.1	113.5	68.8	79.2	79.2	96.9	UN	90.6	UN	*110.4	56.2	106.2	83.3	88.5	32.3	104.2
02 Apr	7.6	———	———	———*	89.5	59.2	48.7	42.1	76.3	UN	76.3	11.8	94.7	17.1	89.5	48.7	61.8	0	115.8
27-28 May	2.0				NP														
11 Jul	3.3				NP					*									
15-16	16.5				123.6	73.9	72.7	35.8	89.1	29.7	69.1	26.7	96.4	29.7	100.0	25.4	94.5	0	91.5
21	1.5				NP														
29	3.8				NP														
31	4.5				91.7	?	60.4	56.2	85.4	70.8	79.2	39.6	100.0	79.2	54.2	56.2	81.2	20.8	75.0
04 Sep	3.2				NP														
24	9.1				M	89.0	58.2	51.6	90.1	28.6	82.4	64.8	73.6	28.6	97.1	23.1	M	M	?
02 Oct	24.4				67.2	45.5	80.3	M	38.9	32.0	87.3	42.6	40.2	66.8	M	75.0	95.5	M	M
30 Nov	31.8				108.2	75.8	65.1	56.9	93.7	33.6	73.0	61.0	45.6	38.4	88.4	45.9	84.6	14.2	96.2
Totals**	179.3	7.1	8.5	12.3	101.3	70.3	71.4	59.0	84.9	33.9	82.6	45.5	80.0	37.8	96.8	56.5	85.5	10.0	99.5

Notation: M = Mechanical malfunction; UN = Untreated; NP = Not pumped (precipitation data from tipping-bucket raingage).
? = Questionable events.
* = Initiation of new treatments, maintenance of catchment, or termination.
** = Percentage totals are based on measured data only; i.e., no estimates.
∔ = Accumulated precipitation events.

Table 4. Summary of runoff efficiencies from wax-treated plots at Granite Reef.

		Wax-treated plots 1/								
Year	Precip.	R-2	T-13	T-7	T-3	T-4	T-12	T-15	T-6	T-8
	mm	% runoff								
1972	244	90	92							
1973	208	87	88							
1974	251	85	2/							
1975	183	88	96							
1976	193	86	91							
1977	116	70	77							
1978	540	81	88	83						
1979	242	76	89	88	63	87	93	90		
1980	293	63/95 3/	90	92	90	90	98	98		
1981	179	98	86	83	71	59	57	100	34	46

1/ First year's data represents partial year.
2/ Missing data.
3/ Retreated during year.

APPENDIX

LIST OF PUBLICATIONS

AND MANUSCRIPTS PREPARED IN 1981

MS. No.

'IRP 20740 IMPROVE IRRIGATION AND DRAINAGE OF AGRICULTURAL LAND (Irrigation and Hydraulics Research Group)

'ublished:

BUCKS, D. A., ERIE, L. J., FRENCH, O. F., NAKAYAMA, F. S. and Pew, W. D. 1981. Subsurface trickle irrigation management with multiple cropping. Trans. Am. Soc. Agric. Eng. Vol. 24(6):1482-1489. 806

BUCKS, D. A., NAKAYAMA, F. S., and FRENCH, O. F. 1981. Keys to successful trickle irrigation: Management and maintenance. Proc. 15th Nat. Agric. Plastics Assoc. Congr., Tucson, AZ. pp. 3-8. 777

BUCKS, D. A., NAKAYAMA, F. S. and GILBERT, R. G. 1981. Is your trickle fickle? Am. Veg. Grower. April 1981. pp 8-10, 68. 832

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CLEMMENS, A. J., and DEDRICK, A. R. 1981. Estimating distribution uniformity in level basins. Trans. Am. Soc. Agric. Eng., 24(5):1177-1180 and 1187. 788

CLEMMENS, A. J., STRELKOFF, T., and DEDRICK, A. R. 1981. Development of solutions for level-basin design. J. Irrig. and Drain. Div., Am. Soc. Civil Eng., 107(IR3):265-279. 795

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NAKAYAMA, F. S. and BUCKS, D. A. 1981. Emitter clogging effects on trickle irrigation uniformity. Trans. Am. Soc. Agric. Eng., 24(1):77-80.	733
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BUCKS, D. A., NAKAYAMA, F. S., and WARRICK, A. W. Principles, practices and potentialities of trickle (drip) irrigation. In Hillel, D. I. "Advances in Irrigation". Academic Press, Inc., N.Y. (In press)	850
CLEMMENS, A. J. Evaluating infiltration for border irrigation models. Agric. Water Management. (In press)	856

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Published:

HATFIELD, J. L., MILLARD, J. P., REGINATO, R. J., JACKSON, R. D., IDSO, S. B., PINTER, P. J., JR., and GOETTELMAN, R. C. Spatial variability of surface temperature as related to cropping practice with implications for irrigation management. Proc. of Fourteenth International Symposium on Remote Sensing of Environment, 23-30 April 1980. San Jose, Costa Rica. 1981. 763

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MILLARD, J. P., JACKSON, R. D., GOETTLEMAN, R. G., and LEROY, M. J. Solar elevation and row direction effects on multispectral scanner data obtained over cotton. 834

IDSO, S. B. Reply to A. J. Crane's "Comments on Recent Doubts about the CO_2 Greenhouse Effect." J. Appl. Meteorol. 835

IDSO, S. B., REGINATO, R. J., and RADIN, J. W. Leaf diffusion resistance and photosythesis in cotton as related to a foliage temperature based plant water stress index. 857

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Prepared:

IDSO, S. B., and KIMBALL, B. A. Man, carbon dioxide, climate and food: A global ecological perspective. 841

IDSO, S. B. Climatic impact of atmospheric CO_2. Science. 853

IDSO, S. B. Non-Water-Stressed baselines: A key to measuring and interpreting plant water stress. 855

PINTER, P. J., JR., and REGINATO, R. J. Thermal infrared techniques for assessing plant water stress. In: Proc. Irrigation Scheduling Conf., ASAE, Chicago, Illinois, 14-15 Dec. 1981. Also submitted to Trans. ASAE. 851

NRP 20790 PREVENTING POLLUTION OF AND IMPROVING THE QUALITY OF SOIL, WATER, AND AIR (Subsurface Water Management Group)

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BOUWER, E. J., MC CARTY, P. L., and LANCE, J. C. Trace organic behavior in soil columns inundated with secondary sewage. Water Res. 15:151-159. 1981. 756

BOUWER, H. Protecting the quality of our groundwater: What can we do? Ground Water Monitoring Review. Vol. 1(2):22-26. 1981. 823

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