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

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TABLE OF CONTENTS

	Page
Predicting Hydraulic Characteristics of Critical-depth Flumes of Simple and Complex Cross-sectional Shapes	1
Surface Irrigation Automation	9
Clogging Potential of Colorado River in Trickle Irrigation Systems and Development of Methods for Preventing Plugging	21
Water-use Behavior of Two Cotton Species	38
Simplifying Neutron Moisture Meter Calibration.	44
Mathematical Modeling of Border Irrigation Hydraulics	51
Development of Remote Sensing Techniques for Agricultural Water Management and Crop Yield Prediction	86
Computer Simulation of Greenhouses	99
Evaluation of CO_2-enriched, Unventilated, Solar-heated Greenhouses	100
Microbiology of Soil and Water Systems for Renovation and Conservation of Water	137
Wastewater Renovation by Spreading Treated Sewage for Groundwater Recharge	143
Column Studies of the Chemical, Physical and Biological Processes of Wastewater Renovation by Percolation Through the Soil	197
Use of Floating Materials to Reduce Evaporation from Water Surfaces	235
Chemical Modification of Soils for Harvesting Precipitation	245
Rainfall, Runoff, and Erosion Relationships from Agricultural Watersheds in Hawaii	259
Appendix - List of Publications	A-1
Personnel	iii

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G. Brooks, Student Aid
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TITLE: PREDICTING HYDRAULIC CHARACTERISTICS OF CRITICAL-DEPTH FLUMES OF SIMPLE AND COMPLEX CROSS-SECTIONAL SHAPES

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

INTRODUCTION:

Long-throated flumes, particularly the hydraulically-related, broad-crested weirs are continuing to be well suited to irrigation canal applications. There is no special size limitation and the extremely low head loss requirements allow them to be retrofitted to most canal systems. The computer-modeling techniques are being used to develop pre-computed tables for common sizes of canals in a wide variety of sizes and shapes. Unlined canals are also included. More complete tables and specifications for both lined and unlined are continuing.

The potential application of the devices are almost unlimited. If a low-cost device were to service from 10 to 100 acres, the potential use would be up to 3 million units for the 35 million irrigated acres that are served by surface systems in the United States alone. On a world-wide basis and probably with smaller average plot sizes, the potential may be 10 times these numbers.

New Designs: Several construction concepts and design sizes were developed during the reporting period. Sheet metal versions of the broad-crested weir style were installed at the Safford Experiment Station, University of Arizona (5 units in three sizes) in 1-ft wide, 1:1 sideslope concrete lined canals, discharging less than 10 cfs. Three more units were installed on a cooperator's farm for evaluation in 2-ft wide, 1:1 sideslope canals discharging up to 50 cfs. These flumes can be built in less than 2-3 man hours each and installed after halting canal flows in less than 1 man hour each. Cost of materials ranges from $20 to $50, depending on flume size. The gage takes about 1 hour to construct. These times are based on availability of complete detailed drawings and the experience of having constructed at least one previous flume, and a 2-man crew.

Portable flumes were designed for use in furrows and for larger flows in some unlined canals. They can also serve to measure tailwater outflows from irrigated fields. A family of 5 dynamically similar flumes were developed to measure maximum flows from 3 liters per second (ℓ/s) for the 75-mm wide sill size to 300 ℓ/s for the 450-mm wide sill size.

Using the mathematical model to produce stage-discharge tables for these flumes, and then applying curve-fitting techniques to the tables, it was found that by manipulating the channel and sill size relationships, a modified power equation with an exponent of 2 could represent the table results. This permits simple field calculation of the discharge without the need for a scientific calculator to handle odd-power functions. The power equation is

$$Q = A(Y + \Delta)^2 \quad (1)$$

Where Q is in liters per second (ℓ/s); A and Δ are constants; and Y is the measured flow depth, in cm, referenced to the top of the sill.

For English units with Q in cubic ft per second (cfs), and Y in ft, use:

$$Q_{cfs} = \frac{10}{0.3048} A \left[Y_{ft} + \frac{\Delta}{0.3048 \times 100}\right]^2 \quad (2)$$

Equation 2 is left in this form to indicate the application of the metric conversion factor of 1 ft = 0.3048 meters. Algebraic manipulations place the conversion units with A and Δ so that for a particular flume the final equation in either system of units is most simple.

Values for A and Δ are shown in Table 1. The flow range for each flume should be limited to Y values preferably between L/20 and L/2. The L values represent the length of throat, Figure 1. Figure 2 shows the construction-layout details. Deviations of the equational values from the computed tables for the flumes may exceed 2% at the extreme ends of the flow ranges. The tables themselves will represent the true discharge to about ± 2%, tending to underpredict the discharge rate at low flows. The equation tends to overpredict the table values at lowest flows, so somewhat compensates. At the highest flows, the equation tends to underpredict by 1 to 2%. The tables are usually most accurate in this range.

The smaller versions are most suited to furrow irrigation applications and experiments. The larger sizes can be used in unlined canals or to monitor outflow from one or several fields.

When fitted with the translocated stilling well, as shown in Figure 1, only approximate leveling is necessary. This is an adaptation of the system used on the "turtle" flume and is described in more detail by Replogle and Clemmens (1979).

"Turtle" Flumes: Details were published in the November-December General Edition of ASAE Transactions (issued in March 1980). (See Replogle and Clemmens, 1979). The patent has been granted and should be issued in April 1980. About a dozen units with 18-inch-long throats (the originals had 12-inch-long throats) were constructed by the Arziona State Office of the Soil Conservation Service (SCS), through a contractor. When these are delivered, a workshop will be set up to train SCS personnel in their proper use.

Concrete Precast Flumes: No new designs were tried, since the sheet metal versions seem more practical then precast concrete in the larger sizes. Of course, the cast-in-place versions are still considered the first choice because they are extremely resistant to damage and vandals. One precast concrete flume has already experienced such damage. One of the precast blocks was stolen.

Designs by Others: A local irrigation district designed and installed a trapezoidal throated flume during the dryup in the fall in what is known as the "Buckeye Feeder Canal". The installation was less than ideal, ending up with more than 0.75 in. fall in its 6-ft length. An approximate correction factor was computed for them until proper construction corrections can be made next fall during the canal dryup.

Three other broad-crested weirs installed during 1978 dryup have subsequently been fitted with proper gages (wrong gages were marked for 2 of them) and are now operating very well.

The Soil Conservation Service and the Bureau of Indian Affairs cooperatively installed a water inventory system on an irrigation project near the Colorado River. Stage recorders were added to about 20 of the broadcrested weirs. Subsequent inspection showed the installations to be very good except that potential problems may occur because the stilling well taps were placed at the extreme bottom of the canal. A better procedure would have been to place the wall tap at a level just below the crest elevation of the sill. This would keep the pipe free of sediment for longer periods between cleanings.

These problems by end users illustrate that there are still technology transfer problems with even the simplest of systems.

The flume design offered for the River Gulp in the Netherlands was installed in the summer of 1979. No subsequent information on performance has been received.

A series of designs for large canals up to 200 cfs were provided to officials in Puerto Rico for their main delivery canals.

A survey of about 35 sites for a study of irrigation water in cooperation with the SCS and BIA was made on the Irrigation District at Parker, Arizona. These flumes, many designed for circular pipes, are to be installed in 1980.

Unlined Canals: The larger units of the portable flumes described above can be used in unlined canals (up to 10 cfs). Because of the wide variety in possible field sizes and shapes of unlined canals, the first recommendation is to line an appropriate section if it can be shaped to a standard lined canal size. If this is not practical, then the present thinking is to line an appropriate length to the existing canal shape and install a rectangular throated broad-crested weir or flume in it. A standard rectangular series of sizes has not yet been computed.

SUMMARY AND CONCLUSIONS:

Portable furrow flumes developed for furrow irrigation studies were used by SCS and SEA/AR personnel during the summer of 1979. Their favorable acceptance led to the design of a series of five metric-dimensioned flumes with maximum capacities of 3 liters per second for the smallest size to 300 liters per second for the largest size. The larger sizes are primarily for tailwater measurements from fields and the smaller sizes are for furrow flow measurements. All are model sizes of each other (dynamically similar). Equations were curve fitted to the computer-generated discharge tables so that either tables or an equation may be used with these sizes. The sizes were chosen to produce equations with a power of 2 so the discharge can be hand-calculated when necessary, or determined with the use of simple, nonscientific calculators. Such a choice is possible because of the mathematical modeling available.

Several special flumes for earth ditches were also designed. Because of the wide variety of possible field shapes on unlined ditches the first recommendation is to attempt lining a short section of the ditch with concrete and installing one of the standard lined canal flumes previously offered. If lining to a standard ditch size is impractical, then the present thinking is to line a section to the most practical shape for the ditch and to install a rectangular flume shape within this. A standard rectangular series of sizes for these have not yet been selecte .

Precomputed flume sizes for small canals that were selected in cooperation with SCS have been further field evaluted for appropriateness. Some revisions in the size selections, flow ranges and detailed dimensions were made and incorporated into a Farmers Bulletin to be distributed in April 1980. Similar information was presented in talks and articles printed in irrigation news media. Flumes for several sizes of large trapezoidal-shaped canals, 3 to 5 ft across the bottom were designed for flows up to 200 cfs for irrigation districts in Puerto Rico, and are now available for use in western states with similar sizes. Sheet metal broad-crested weirs were installed in three medium-sized canals discharging up to 50 cfs. The weirs, which are a type of long-throated flume, were pre-constructed for field installation. The canal flows were halted for a few minutes to accomplish the installations. Five more were constructed in three sizes for small canals with less than 10 cfs and installed on the University of Arizona Experiment Station at Safford, Arizona.

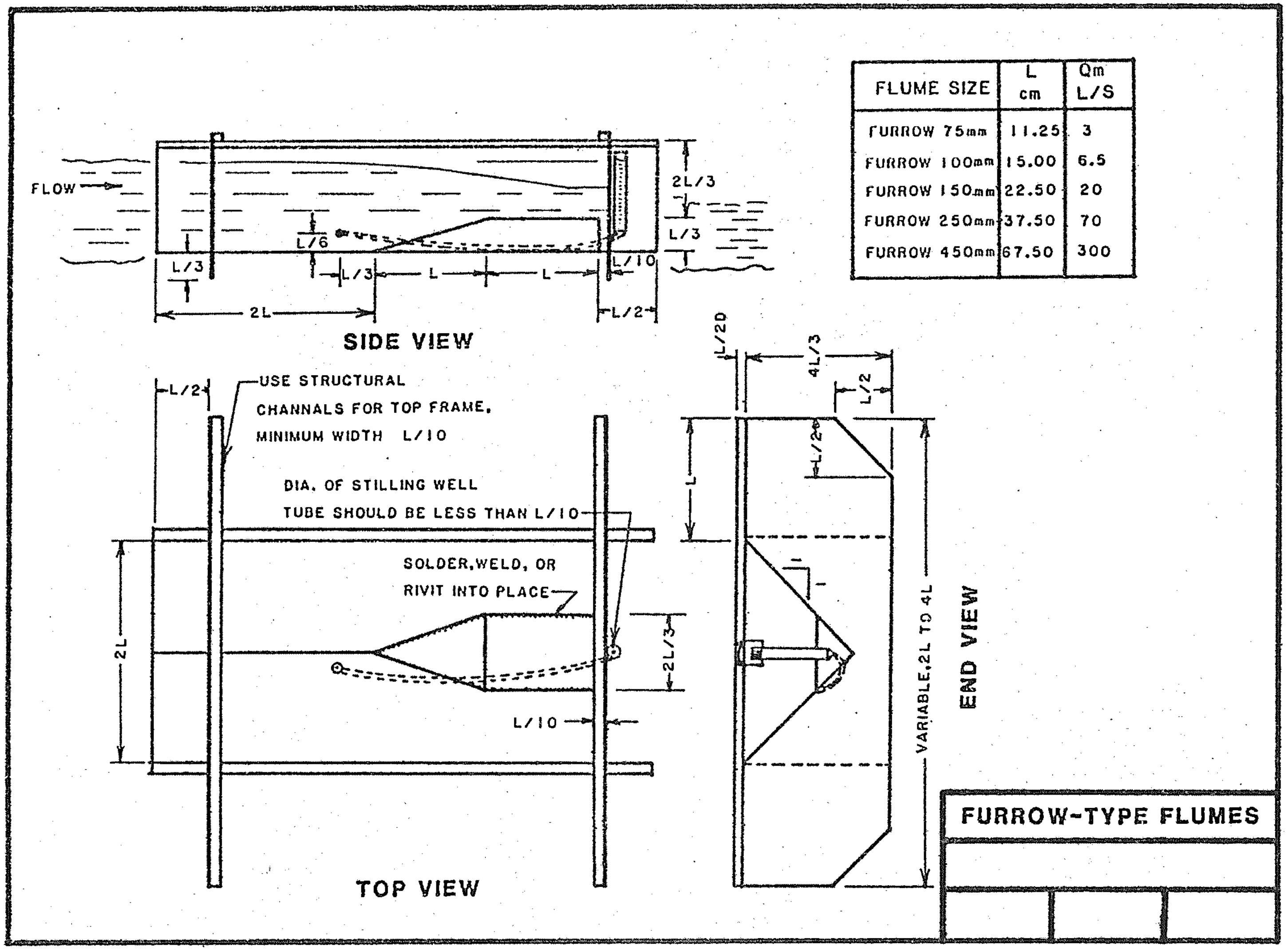
PERSONNEL: J. A. Replogle, A. J. Clemmens

REFERENCES:

1. Replogle, J. A., and Clemmens, A. J. 1979. Broadcrested weirs for portable flow metering. Trans. Am. Soc. of Agric. Eng. Vol. 22(6): 1306-1309.

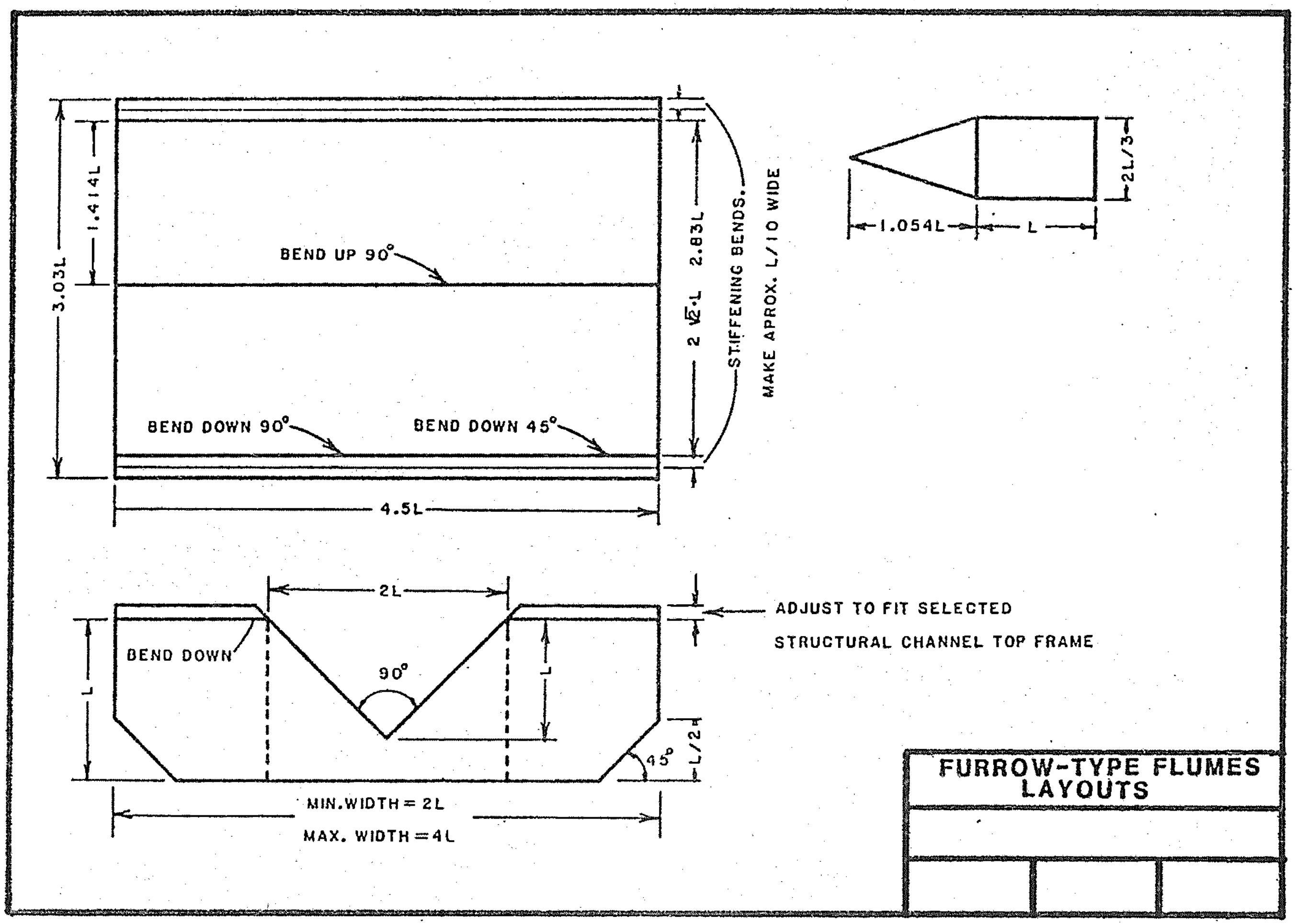
Table 1. Furrow Style Flumes -- Metric Units.

Flume Size	Δ	A	Constr. depth cm	Y_{max} cm	Q_{max} ℓ/s
75 mm	.17228	.09293	7.5	5.5	3.0
100 mm	.24399	.10733	10.0	7.5	6.5
150 mm	.38964	.13146	15.0	12.0	20.0
250 mm	.68424	.16977	25.0	20.0	70.0
450 mm	1.30761	.22575	45.0	35.0	300.0



FLUME SIZE	L cm	Qm L/S
FURROW 75mm	11.25	3
FURROW 100mm	15.00	6.5
FURROW 150mm	22.50	20
FURROW 250mm	37.50	70
FURROW 450mm	67.50	300

Figure 1



3.03L
1.414L
BEND UP 90°
BEND DOWN 90°
BEND DOWN 45°
2.83L
2 √2·L
STIFFENING BENDS.
MAKE APROX. L/10 WIDE
4.5L
1.054L
L
2L/3
2L
ADJUST TO FIT SELECTED
STRUCTURAL CHANNEL TOP FRAME
BEND DOWN
90°
L
L
L/2
45°
MIN. WIDTH = 2L
MAX. WIDTH = 4L
FURROW-TYPE FLUMES
LAYOUTS

Figure 2

TITLE: SURFACE IRRIGATION AUTOMATION

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

INTRODUCTION:

Surface irrigation, because of its low water distribution energy requirements compared to pressurized systems, merits intensified attention. If, however, surface irrigation techniques are to be used successfully in the future they likely must be operated automatically. Automation, as an irrigation management tool, assures more precise control of the quantity of water applied. It can result in water savings and crop yield improvement by minimizing prolonged inundation time and crop scald. In the future, reduced farm labor requirements may be as important as improved irrigation water control.

Most of the work at this location to date has been associated with large flow rate (large gates) and adaptations of automatic controls to existing gates. Future research and demonstrational studies will include design of equipment for small farms with an emphasis on development of gates that are suited to automation. In all cases, the devices used must be simple to operate, reliable and economical. Installation procedures will be developed and maintenance requirements of the systems will be determined.

OBJECTIVES:

To provide to surface irrigation, convenient automated flow control systems that will efficiently use water and energy resources. The systems must be cost-effective and reliable enough to achieve widespread adoption on both large and small farms which use a variety of water supply sources and sizes.

REVIEW OF LITERATURE:

Automatic irrigation gate operation, as used in this outline, means a series of gates or water turnout devices that are operated remotely to divert water into basins or borders from a canal common to all basins. The actuation is according to some predetermined schedule which may be either time, time/distance (length), or water-quantity controlled.

Pneumatic valve systems, hydraulically-controlled butterfly valves, pneumatically-operated lift-gates, reinforced butyl rubber dams, hydraulic pressure gates, and drop gates all have been or are being evaluated for automating surface irrigation systems. We have used automated control equipment successfully for nearly 5 years on two sites. The pneumatic controls and actuators have been featured on lift-gates and on concrete ports for surface distribution systems.

At the request of the Soil Conservation Service, the first cost-shared automated irrigation system was designed and installed as part of the on-farm irrigation improvement program administered by the SCS in the Wellton-Mohawk Irrigation and Drainage District in southwestern Arizona. The system was installed in May 1977, and has been in service since that time. Twenty-three lift-gate turnouts and two lift-gate checks were automated, using pneumatically-operated cylinders.

PROCEDURE:

Improve and develop gates, actuators, signaling devices, control center components, and power sources considering cost, simplicity, and reliability. Procedures will involve construction or adoption of new or improved devices followed by adequate field evaluation. Investigate extending single field automation to automatic control of all irrigation on a farm unit and finally, implementation of automatic controls on an irrigation district-wide basis. Assist the Soil Conservation Service, private consultants, and equipment distributors in design and installation procedures for automated systems. Encourage commercial development of automated equipment components.

RESULTS AND DISCUSSION:

A summary of the automated irrigation systems that we have been associated with in the Wellton-Mohawk Irrigation and Drainage District since 1975 is shown in Table 1. Five fields have been automated through 1979--the original two were, at our request to the cooperating farmers, for research and demonstrational purposes while the last three are operational systems for which we have provided design information and installation assistance. The latter three systems, though operational, have also been used for research/development. Three additional systems are being planned during 1980 which again are for on-farm use but new ideas for gate signaling will be tried, volumetric control will be used on at least one of the systems, and installation procedures will be simplified.

Woodhouse Automation--Lift-gates

The system was used during 1979 which completes nearly 5 years' operation. Air bypass within the cylinders was checked in September 1979. The air cylinders still bypass very little air which indicates that the U-cup seals of the pistons are still functioning properly. The pneumatically-operated 4-way valves attached to the gates continue to operate satisfactorily.

Naquin Automation--Lift-gates

Alfalfa was irrigated during 1979 using the automated port system. The system functioned satisfactorily with the port closures redesigned to minimize debris collection.

New closure structures for all ports except those leading to basin 3 were designed and built here at the U. S. Water Conservation Laboratory and installed in February 1979. The modification/design included eliminating one of the four support legs, turning the structure 45°, and hanging the closure plate from the upper leg. The turnouts were inspected after an irrigation in April in which weeds and moss were being carried in the water. Of the 28 modified structures in use, only two would not close even though debris still caught on the legs of the structures. Three of the six not modified (originals) would not close. This one sampling showed a closure improvement from 1 in 2 to 13 in 14. Occasionally, the irrigator would still be required to clean the structures but they would likely close during the irrigation.

The air pillows used on basins 5 and 6 were leaking considerably by the fall of 1979 and were replaced by air bellows in November. The leakage was from various sources--some from holes, but mainly deteriorating fabricated joints. The deterioration had been occurring gradually over a period of 2 or 3 years. We changed to the air bellows since they have not leaked during the 4 years' service on basins 1, 2, 3, and 4; and they are commercially available.

McDonnell-McElhaney #1

1979 completed 3 years' operation of the automated system. Generally, the system has worked satisfactorily with the main problem being mice chewing the polyethylene tubing at the overflows two or three times during the 3 years. Even though a tube may be chewed, the system is still operable since the air compressor used can keep up with the air loss.

Canvas sleeves were placed over the air cylinder rods in January to serve as a protective shield against a rust-type buildup. The rods were cleaned and lubricated at the same time. No buildup has occurred since the sleeves were installed. I am recommending that sleeves be used on all rods in the future. Cost was $2.50 each.

Shuttle valves used in conjunction with the overflow selection system at various gates worked satisfactorily as explained and illustrated in the 1978 annual research report.

McElhaney and McDonnell will be automating another field in early 1980 (MM #2). The control center will be used on both systems. This will require some modification at the control panel of MM #1 which involves a digital controller, matrix selection panel, and electrical/pneumatic conversion using solenoid-operated air valves. The new system will include 9 basins to irrigate 76 acres. Equipment for volumetric control of the irrigation will be tried on MM #2.

Hoffman Automation

At the request of the Soil Conservation Service, two more automated systems were designed and installed. The fields, both owned by Joe Hoffman, are located 20 miles apart. The first field (JH #1, 110 acres) is divided into 8 basins, 4 on each side, of the nearly 3000-ft concrete-lined canal, Figure 1. The second field (HE #1) features 12 basins on nearly 80 acres, Figure 2. Canal length in the second field is just over 2000 ft. Both systems use lift-gates (jackgates) as single inlets to the individual basins.

The two primary differences between these systems and any done previously are (1) the electrical wire and air tubing was directly embedded in the concrete lining (for gopher protection) during the slipforming operation, and (2) a portable control center was used that is independent of 110 VAC power.

Embedding procedure of the electrical wire and polyethylene tubing (5/16-inch O.D.) was described in the 1978 annual report. The canal on JH #1 was lined in December 1978 and took about 6 hours. HE #1 was lined in February 1979 and took 3 1/2 hours. Placement of the wire and tubing caused very little delay in the canal lining operation. The embedding operation was successful and all wires and tubes were functional after installation. Three signal wires were open, however, when JH #1 was tested on 8 May 1979. These were to gates 4, 6, and check gate 2, Figure 1. We tried to determine the cause of the failure but we were unsuccessful. The following observations were made: (1) All three wires were along the east side of the canal; (2) the wire was not direct burial, single conductor wire as used for most of JH #1 and all of HE #1, but was a polyethylene-jacketed, stranded wire; and (3) the jacket material was swelled at the crack lines and in some instances the crack lines were cut down to the wires/tubing while at HE #1 no crack line was made across the top edge of the lining. New wire and tubing were installed in August 1979 on JH #1. Tubing and wire were encased in 1 1/4-inch schedule 125 PVC pipe and placed in a shallow trench along the east side of the canal. This installation provided a good measure of time required to complete various aspects of the job, Table 2.

The embedded wire and tubing at HE #1 remained functional through 1979 and will be closely observed for problems in the future.

The portable control center with bottled air or nitrogen gas and battery power was used for both JH #1 and HE #1. Excessive air leakage around the cylinder rods was a problem. The cylinders were mounted with the rods up so that they would be retracted between irrigations for protection against weathering. Inherently, the rod end of the cylinder will leak more than the non-rod end when pressurized. In addition, dust accumulated around the rod and was pulled into the seal, which caused more leakage. The cylinders will be remounted with the rod end down (rod extended when gate closed) during 1980. We expect the air use to be such that Hoffman can get two irrigations from each bottle of air or nitrogen gas.

System design features:

(1) The irrigator can select either automatic or manual mode of operation within the control trailer. The manual operation by toggle switches is useful if the controller should become disabled.

(2) Relays (DPDT) are used to signal actuation of the check gates, Figure 3, dependent on basin gate operation.

(3) Toggle switches (three) are located at each gate to allow irrigator selection of overflow gates and irrigator actuation of the gate without returning to the control center--open gate if in closed position or close gate if in open position, Figure 4.

(4) Wire size was selected for a battery input of 25 vdc and with an under voltage to the 24 vdc solenoids of 15%. Hence, allowable voltage drop was 4.6 volts. Solenoid amperage was 0.32 amps. Maximum wire lengths: 18 ga, 1100 ft; 16 ga, 1750 ft; 14 ga, 2800 ft. Power and ground wire size was dependent on number of gates that would operate when an overflow was sensed, and is site specific. For both of the Hoffman systems, 12 ga wire was adequate.

(5) Helical springs were designed to provide gate openings of 13 to 14 inches. Spring characteristics were: spring force at 20-inch displacement is about 560 pounds (spring factor (k) = 28 lbs/inch); free length 27-28 inch; coils, total 35, active 33; wire diameter 0.225 inch; spring I.D. = 1.30 inch; material 17-7 stainless steel. The actual gate opening measured in the field was about 15 inches.

SUMMARY AND CONCLUSIONS:

Five fields of level-basins have been automated through 1979 in the Wellton-Mohawk Irrigation and Drainage District. The original two (Woodhouse and Naquin) were at our request, and were for research and demonstration purposes. The last three (McElhaney-McDonnell, Hoffman --two systems) are operational systems for which we have provided design information and installation assistance. Even though the latter three systems are operational they have been used for research, development, and evaluation purposes. Items such as (1) control center independent of 110 VAC power; (2) bottled air or nitrogen gas used to power gates; (3) encasement of electrical wire and air tubing for gopher protection in concrete, during lining of the canal and two techniques of placement in PVC pipe; and (4) air cylinder placement/rod protection, have all been research/development items over the past 3-year period.

To date about 390 acres have been automated which has included 59 basins, 9 check gates, and 14 safety overflows. Three more systems are planned for 1980, which would bring the total acres automated to 756.

Changes to the Naquin system during 1979 included a redesign of the port closures and replacement of the air pillows with air bellows. The port closure modification improved the closure reliability to a more satisfactory level. The air pillows had developed leaks over a period of 2 to 3 years. They were replaced with bellows since bellows have worked well for the entire test period and they are commercially available.

Canvas sleeves placed over the exposed cylinder rods in the McElhaney-McDonnell system controlled rust-type buildup that had been a problem during 1977 and 1978. I am recommending that these inexpensive sleeves be used on all future installations.

One of the two systems in which the electrical wire and polyethylene tubing was embedded into the concrete failed shortly after installation. We were unable to determine the cause of failure but noted that the three wires that failed were on the same side of the canal. The wire was polyethylene-jacketed-stranded rather than solid-single-conductor direct burial as used on the other system, and the crack lines extended to the wire and tubing in several instances. This system was rewired and replumbed in August 1979 by encasement in 1 1/4-inch PVC pipe. The second system, where the wire was in the concrete, continued to operate through 1979.

The air cylinders used on the two Hoffman systems leaked excessively around the cylinder rod, mainly due to dust/debris pulled into the rod seal. The cylinders will be remounted in 1980 with the rod end down and with canvas sleeves to protect the rods. We expect the air use, after this change, to be such that Hoffman can get two irrigations for each bottle of air or nitrogen gas (less than 5 cfh air use).

Three additional systems are being planned during 1980 which again are for on-farm use. Again research/development will be part of these systems: new ideas for gate signaling will be tried, volumetric control will be used on at least one of the systems, and installation procedures will be simplified.

Personnel: Allen R. Dedrick

Table 1. Tabulation of 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	70	8	3	3
1977 2/	McElhaney & McDonnell #1	64	23	2	4
1979 2/	Joe Hoffman #1	110	8	2	3
	Hoffman Enterprises #1	80	12	1	2
	Subtotal	389	59	9	14
1980 2,3/	McElhaney & McDonnell #2	76	9	4	5
	Hoffman Enterprises #3	187	20	10	9
	Hoffman Enterprises #4	104	14	5	6
	Total	756	102	28	34

1/ Research/Demonstration at USDA-SEA-AR request.

2/ Operational systems, cost shared by SCS.

3/ Proposed for installation during 1980.

Table 2. Time and manpower required for installation of electrical wire and tubing for rewiring and replumbing of JH #1 automated system in August 1979.

Job	Crew Size	Time, Hours	Man-hours	Rate
Trenching, 12" deep, 3075 ft	1	14	14	220 ft/hr
Encasing, 3075 ft 1/	7	3.5	24.5	
	4	1	4	
			28.5	110 ft/hr 2/
Total Job 3/	4-7		182	1.65 man hr/acre 4/
				0.60 man hr/ft 5/
				18 man hr/gate 6/

1/ 40-ft lengths of PVC pipe were walked on to the wire and tubing which had been laid along the toe of the canal fill. All joints were solvent welded.
2/ Rate of encasing at McElhaney-McDonnell #1 in 1977 using split PVC was 65 ft/hr.
3/ Included electrical wire and polyethylene tubing hookup to gates, installation and hookup to control panel, grouting of PVC pipe into structural crossings at gates, and installation of junction boxes at each checkgate.
4/ 110 acres.
5/ 182 man-hrs/3075 ft.
6/ 10 gates

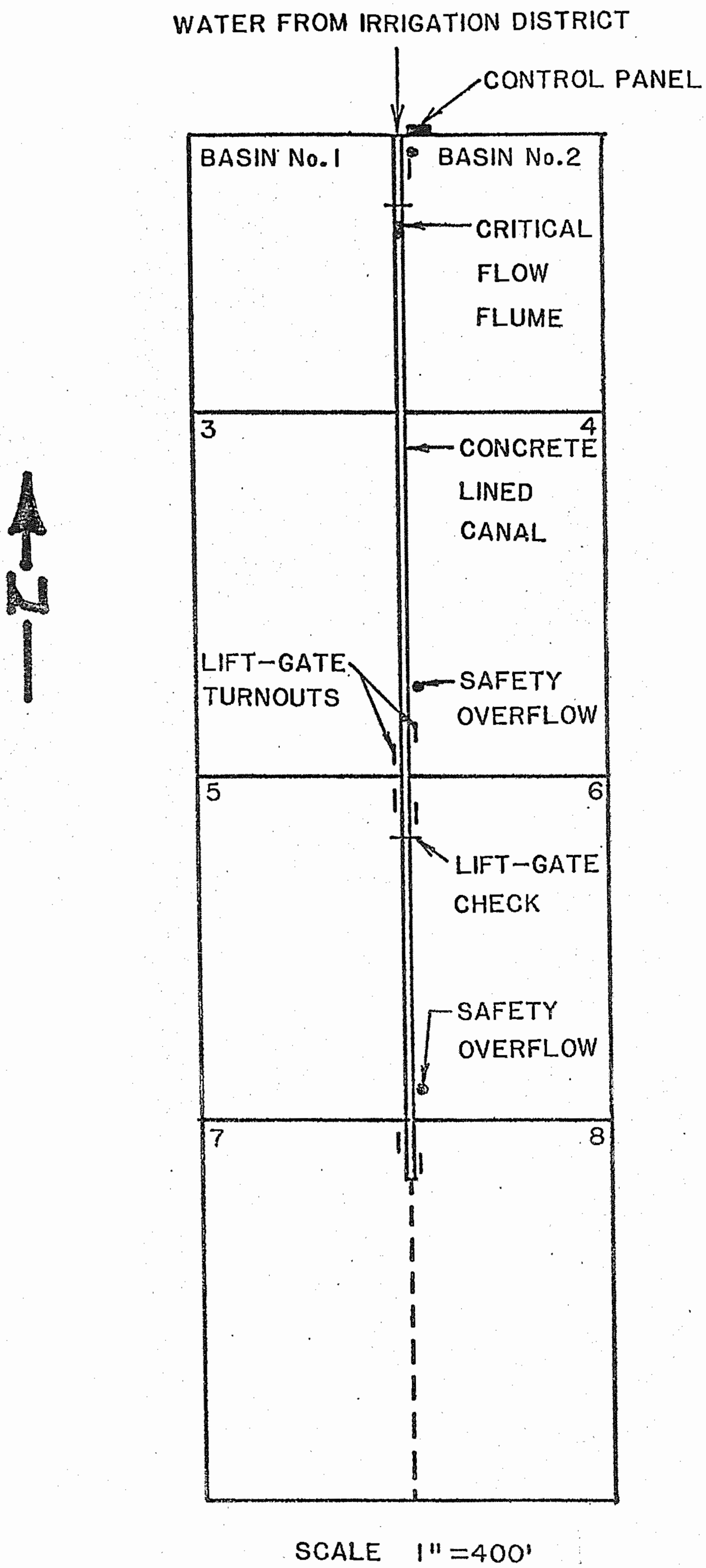


Figure 1. Field layout for automated irrigation system on Joe Hoffman farm (JH#1), 8 basins, 110 acres, concrete lined canal about 3000 ft long.

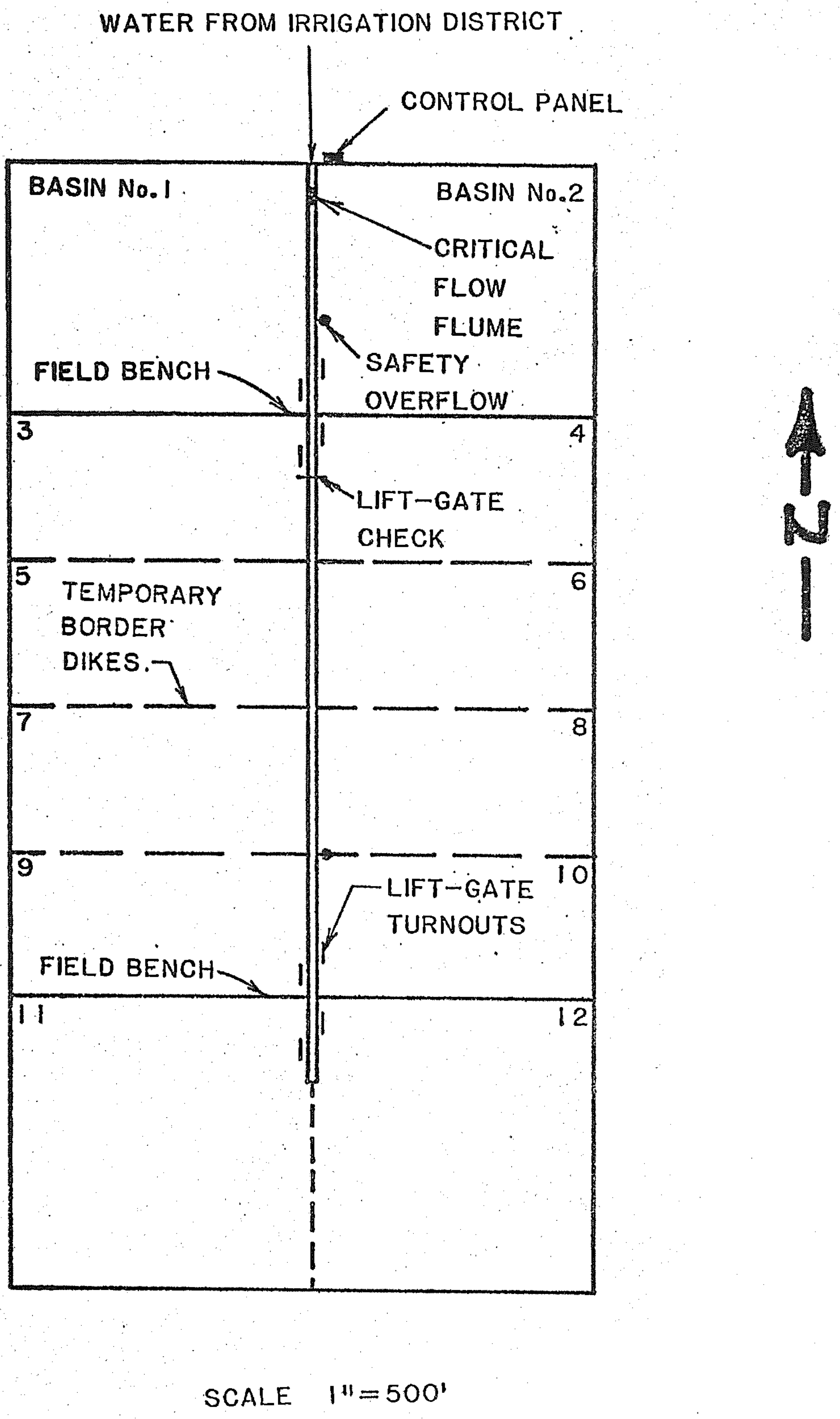


Figure 2. **Field layout for automated irrigation system for Joe Hoffman (HE #1), 12 basins, 80 acres, canal about 2000 ft long.**

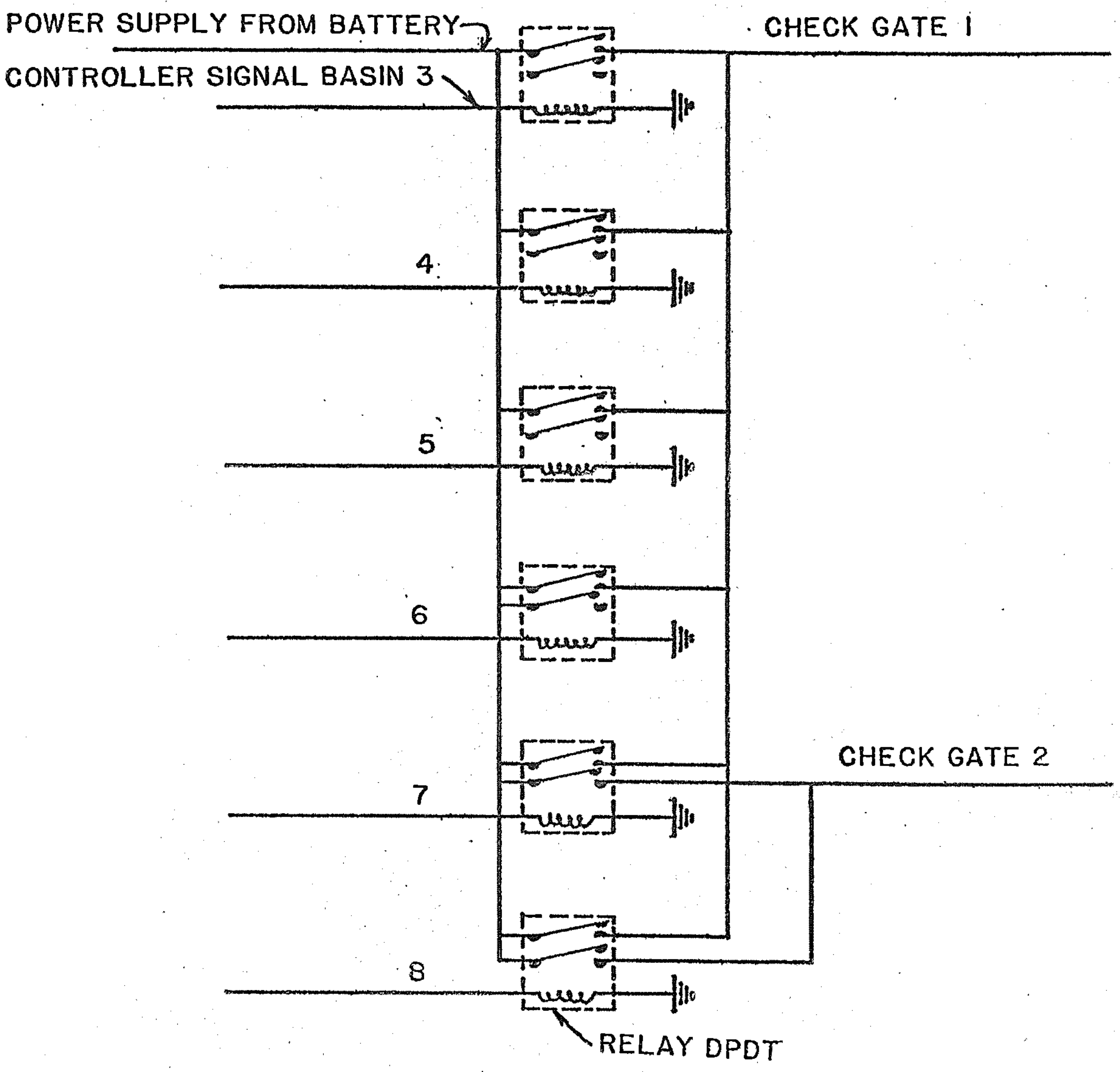


Figure 3. Schematic diagram of lift-gate check actuation on Joe Hoffman automated system (JH #1).

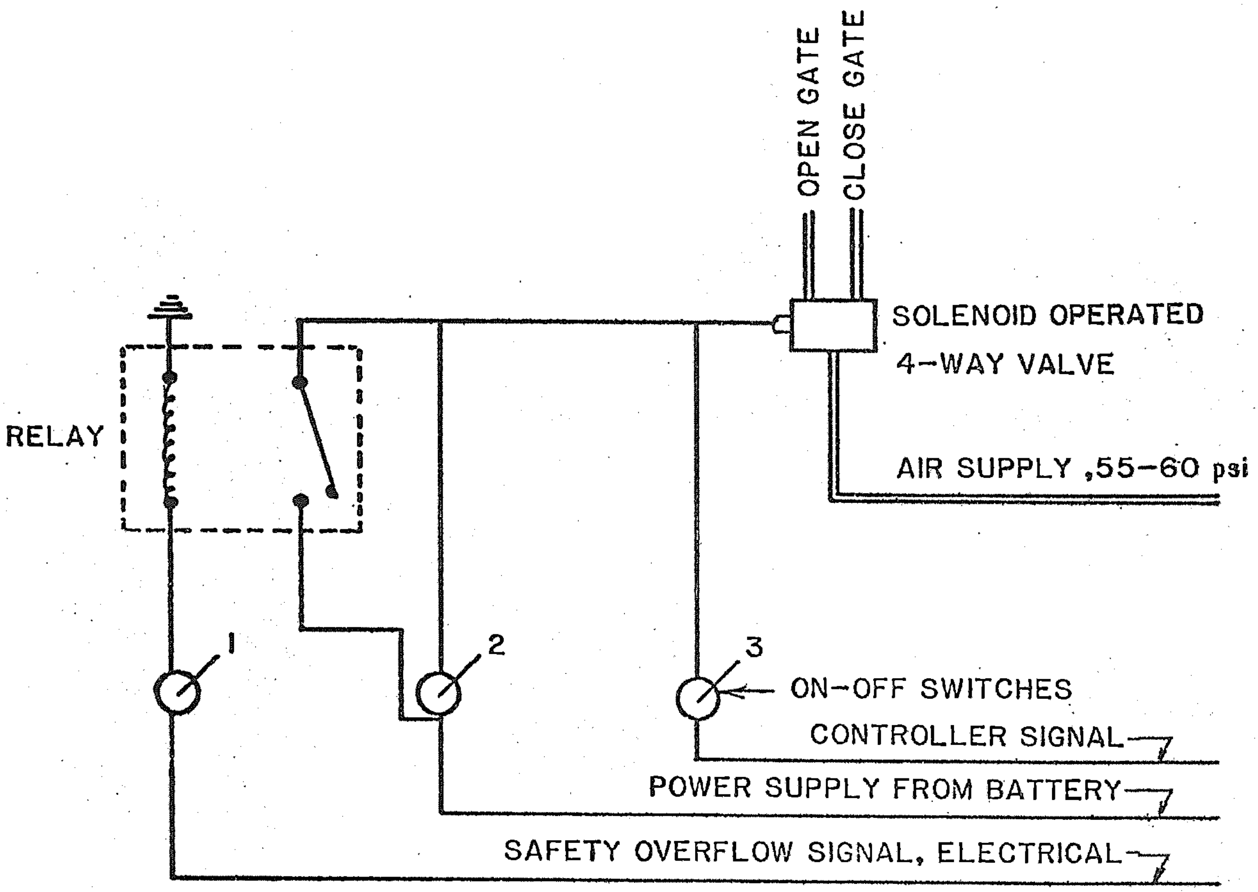


Figure 4. Schematic diagram of overflow gate selection and irrigator interrupt equipment located at each gate on the Hoffman systems installed during 1979. All electrical power is 24 vdc. The relay is DPDT. Switch 1 on, gate opens if safety overflow signal is received. Switch 2 on, gate opens when in closed position. Switch 3 on, gate closed until receives controller signal; off, gate can not receive controller signal--serves to close gate if desired by irrigator if in open position.

TITLE: CLOGGING POTENTIAL OF COLORADO RIVER IN TRICKLE IRRIGATION SYSTEMS AND DEVELOPMENT OF METHODS FOR PREVENTING PLUGGING

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

INTRODUCTION:

The field work at Tacna, Arizona, on emitter clogging started in January, 1975 was terminated in April, 1979. It would have been profitable from the experimental standpoint to have continued the work through the summer, but the land was transferred to a new purchaser who wished to convert the farming operation to his needs.

The simulation model started in 1978 that related clogging to water application uniformity was expanded further and completed.

PROCEDURE:

Part 1.

Individual emitter flow rates were measured for all the emitter types and treatment combinations which are listed in Table 1. Following this, the entire trickle system was dismantled and the emitters showing abnormally fast, no discharge, and 50% reduction from the initial rates were taken into the laboratory for more detailed inspection. Some were dissected and inspected under the microscope to find the basic cause or causes of discharge rate change. Other emitters were sampled to identify the microbial species contributing to the clogging problem.

Part 2.

In the clogging simulation modeling study, additional computations were made to derive some practical meaning on how clogging affects irrigation uniformity in the field.

RESULTS AND DISCUSSION:

Part 1.

Final measurements and subsequent computations made on the flow characteristics of individual emitters after 4-1/3 years of operation are presented in Table 2. Emitter 2 was entirely free of complete clogging in all water treatments including the screen-alone filtration (Treatment A & B) where five of the different emitter types had major clogging problems. The average discharge rate for No. 2 had decreased by approximately 25% and coefficient of variation (CV) by 3- to 5-fold. The smallest change in discharge rate and CV occurred in the acid-alone treatment F. Microbial analysis, however, showed that this treatment had the highest microbial population. Thus microbial population alone is not a reliable criteria for use in predicting emitter clogging.

Emitter 7, like Emitter 2, had no clogging in Treatments C, D, E, & F with the sand filtration water treatments, but unlike Emitter 2, drastic reduction in discharge rate occurred within 3 months of emitter installation and operation in Treatments A & B with screen filtration alone treatment. This emitter was not used in any of the screen-alone filtration treatments subsequent to this finding. Emitter 7 with acid and sand filtration F was least affected by clogging problems similar to Emitter 2.

Only a few completely clogged emitters were present for the Emitter 4 design, but in this instance, a large 2- to 4-fold increase in discharge rate occurred in the hypochlorite treatments D & E. These emitters had to be replaced two times during the 4-1/3-year experimental period with various types of formulations for the internal, flow controlling membrane. Microscopic examination following the first observed problem had indicated that the rubber-like membrane was deteriorating with the hypochlorite treatments. Emitters of the same construction, but with an initial discharge rate of 8 ℓ/h (2 gph) also exhibited an increase in discharge rate with hypochlorination. The third and last set of 4 ℓ/h (2 gph) emitter replacements started to show a decrease in discharge rate rather than an increase. In the acid-treated situation, the original emitter continued to operate satisfactorily over the 4-year period. Microscopic examination, however, indicated that the internal membrane was beginning to deteriorate similar to the hypochlorite-treated membrane, so that eventually the discharge rate should begin to increase.

Emitter 3, a lower discharge rate version of Emitter 2, operated less satisfactorily than Emitter 2. Again, the continuous acid treatment F emitters had the best operating characteristics for the various water treatment combinations. Also, the acid-hypochlorite chemical treatments appeared better than the no chemical treatment. With both emitters 2 & 3, the manual-flush capability of the emitter design was not used. Possibly for Emitter 3, using this feature could have decreased the number of completely clogged emitters and improved on the final emitter performance.

Emitter designs 1, 5, 6, and 8 had the least satisfactory performance after 4 years operation even when the various chemical treated waters were used. Apparently high enough suspended material got to the internal structure to cause a malfunction that could not be controlled with chemicals. In the early phases of the study, the emitters with the chemical treatments appeared to operate better than the untreated ones, but the gradual accumulation of particulate materials overcame any advantage of the chemical control present initially.

The various causes of clogging based on microscopic examination of emitters with reduced discharge rates of less than 50% of the initial rate are listed in Table 3. Physical factors contributed to more than 55% of the total clogging. Of practical significance is the large contribution of the plastic particles to the clogging problem (26% or almost one-half of the total physical clogging). This indicates that extra care should be taken in flushing the system to remove the particles right after construction and before the emitters are inserted into the supply lines. In addition, repairs or alterations to the system should be made without introducing the plastic cuttings into the lines.

Microbial and chemical factors played a minor role in the clogging problem for this water. This would be expected in part because water treatment with hypochlorite and acid was used to control these factors. The various types of microbes present in the water and sediments from the emitters and laterals are listed in Table 4. Only the predominant seven of the 19 types of bacteria are presented here. The dominant bacterial type present throughout the trickle system was *Pseudomonas* sp., particularly in emitters clogged with microbial slime. The slime-like material under normal observation appears yellow to light-brown in color and the data indicated that the *Flavobacterium* sp. contributed to the yellow pigmentation and that this species growth was supported by the non-pigmented *Pseudomonas* sp.

SUMMARY AND CONCLUSIONS:

The successful operation of long-term trickle irrigation systems requires proper water treatment and selection of emitter type to fit the composition of the treated water. With the Colorado River water used in the 4-year study, the physical factor predominated over the microbial and chemical factors in the clogging problem so that filtration to remove the suspended load should be of prime consideration in water treatment. Emitter clogging was also found to be caused by plastic cuttings created during the installation and repair process, indicating that care should be taken to minimize the introduction of such materials into the lines.

Emitter types with moving parts or membrane were found to be more susceptible to malfunction than those with static devices. In this case the discharge rate could be higher or lower than the initial value depending upon the manner in which the malfunction was created. Those with flexible membranes failed after exposure to hypochlorite chemicals causing an increase in discharge rates. For emitters that were unaffected by material decomposition, acid treatment to adjust pH to 7 and less was about as effective as the hypochlorite-acid combination for maintaining the discharge rate.

Part 2.

The effect of clogging on the various types of uniformities (defined in Appendix A) with two different initial coefficients of variation (CV_i) of 0.05 and 0.10 are presented in Tables 5 and 6. The computed CV_f values indicate the obvious benefit of having a lower initial CV_i (Table 5 versus Table 6) and of using multiple emitters per plant. With four or more emitters per plant, CV_f values of 0.05 to 0.10 are not reached until a clogging rate of about 5% is reached. At 5% clogging and greater, the computed CV_f values are similar between the systems starting with CV_i values of 0.05 and 0.10 and thus, little advantage is gained by using emitters with the lower CV_i values.

The average discharge rates for the lower 25% ($\overline{X}_{25}$) and the upper 12.5% ($\overline{X}_{12.5}$) are listed in Table 7. These were obtained by sorting the hypothetical population in orderly descending sequence and combining the various groups of flow rates. The emission uniformity (EU) and absolute emission uniformity (EU_a), defined by Karmeli & Keller (2), presented in Tables 5 and 6, were computed from these averages. Christiansen's uniformity coefficient, UC_c, (1) which considers absolute deviations from the average over the whole populations, is higher than EU_a, which accounts for averages of the lower one-quarter and the upper one-eighth portions of the population. Based on hydraulic considerations without accounting for clogging, Karmeli and Keller (2) recommended an EU_a minimum of 90, which would give a discharge variation of about 10%. This would mean that the value of UC_c should be about 95%. In either case, to meet this 90% criteria, the maximum clogging that is tolerable is about 2% with 2 emitters per plant, 4% with 4 emitters per plant and 6% with 8 emitters per plant, with a CV_i of 0.05. Within this clogging range, the percentage of tolerable clogging for a CV_i of 0.10 is about one-half of that for a CV_i of 0.05.

A comparison of the average discharge rates of the subgroups to the overall average should show how the efficiency of water application changes with clogging. This visual comparison may be easier to relate to field situations, rather than discussing uniformity strictly in terms of coefficient of variation, uniformity coefficient and other terms associated with uniformity. Figures 1, 2, and 3 illustrate the effect of clogging of flow rate distribution for 2, 4, and 8 emitters per plant, respectively. Each emitter grouping from 1 to 20 includes 5% of the total emitter population. The horizontal line at the discharge ratio of 1 represents 100% efficiency with respect to water application. Since the emitter discharge rate is normally distributed, some groups will have lower and some higher values than 1, and the extent of the variation from the horizontal would depend upon the value of the coefficient of variation.

These figures can also be related to irrigation adequacy. If the ratio is multiplied by the optimum depth of water application, then any value greater than 1 would represent over-irrigation and any value smaller than 1, under-irrigation. The ordinates of the figures were purposely reversed to represent increasing depth of water application in the downward direction.

In the example of Figure 1, (2 emitters/plant; CV_i=0.05) with no clogging, 5% of the highest discharging emitter combinations will over-irrigate by about 8%, and conversely, because of symmetry, 5% of the lowest discharging emitters will under-irrigate by 8%. If the irrigator wants to decrease the chance for under-irrigation and uses $\overline{X}_{25}$ to schedule his irrigation application time, Curve A would result, indicating the situation where more of the plants were being over-irrigated by a constant ratio. By redesignating the ratio abscissa to any preselected reference average discharge rate, the irrigator can obtain indication of over- or under-irrigation. Ironically, clogging can actually cause over-irrigation.

Irrigation is based on a volume water application per unit area and the irrigator will apply a specified amount of water for a given cycle. The plants with clogged emitters will not be receiving their share of water, whereas those not clogged will be getting more than their adequate share. With 1% of the emitters clogged, there is only a small deviation of the ratio curve from the initial unclogged situation, but the lowest flowing 5% of the emitter group has an average flow rate of 0.76 of $\overline{X}_{avg}$. The increase in clogging from 1 to 5% results in even a more drastic change in discharge rates. In this case, the lowest 10% of the total emitter groups has about one-half the average discharge rate. The $\overline{X}_{25}$ for this is 1.53 volume per hour and if irrigation timing is based on this discharge rate, then the lowest 10% would be about 60% of $\overline{X}_{25}$ and the highest 10% of emitter flow rates about 40% larger than $\overline{X}_{25}$.

With more emitters per plant, (Figs. 2 and 3), the deviation becomes smaller, but the basic implication is that clogging affects not only the adequacy of irrigation to the plant, but also the uniformity of water application.

Clogging of emitters was randomly selected so that this model is not suitable for situations where emitters clog more frequently in one part of the trickle system than in another. Partial clogging was not taken into account, but this condition can be readily adapted into the simulation model.

The model did not consider the practical hydraulic implications of clogging. In a general way, we can see that emitter clogging can lead to over-irrigation since the remaining, normally functioning emitters would be subjected to an increase in line pressure.

The computer results re-emphasize the need to maintain clog-free emitters. Since fertilizers and other chemicals are applied with trickle systems, the application uniformity of these materals coincides with that of water. The question is unanswered as to how redistribution of water and chemicals can moderate part of the nonuniformity. Yield prediction models for trickle irrigation that rely on uniform water distribution can be improved by accounting for clogging.

SUMMARY AND CONCLUSIONS:

Field investigations have shown that the successful operation of long-term trickle irrigation systems must consider both water quality and emitter design. Emitters with moving parts or membrane tended to be more susceptible to malfunction than those with static devices. Besides clogging, increased discharge rate were exhibited by the malfunctioning emitters. The four-year study with the Colorado River water showed that the physical factor predominated over the chemical and biological factors where clogging was involved. To avoid buildup of particles in the lines, flushing should be made an integral part of system maintenance. Plastic cuttings contributed also to clogging and special precautions should be taken during construction and repair to keep these materials out of the system. Acid treatment alone to lower the pH between 6.5 to 7 was about as effective as the hypochlorite-acid combination in maintaining emitter performance.

A simulation model for demonstrating the effect of emitter clogging on water aplication uniformity was further developed. The model shows that the uniformity and adequacy of water application is greatly affected even when the extent of clogging is in the order of 5%. This further emphasizes the need to maintain clog-free, adequately functioning emitters.

PUBLICATIONS:

1. Gilbert, R. G., Nakayama, F. S. and Bucks, D. A. 1979. Trickle irrigation: Prevention of clogging. Trans. Amer. Soc. Agric. Engin. 22(3):514-519.

2. Nakayama, F. S., Bucks, D. A., and Clemmens, A. J. 1979. Assessing trickle emitter application uniformity. Trans. Amer. Soc. Agric. Engin 22(4): 816-821.

3. Bucks, D. A., Nakayama, F. S., and Gilbert, R. G. 1979. Trickle irrigation water quality and preventive maintenance. Agric. Water Manag. 2(2):149-162.

PERSONNEL: F. S. Nakayama, B. A. Rasnick, D. A. Bucks, O. F. French, R. G. Gilbert

REFERENCES:

1. Christiansen, J. E. Irrigation by sprinkling. California Agric. Expt. Sta. Bull. 670. 1942.

2. Karmeli, D., and J. Keller. Trickle irrigation design. Rain Bird Manufacturing Corp. Glendora, CA. 132 pp. 1975.

APPENDIX:

UC_c = Uniformity coefficient of Christiansen (1942):

$$100 \sum_{i-1}^{k} \left| X_i - \bar{X} \right| k\bar{X},$$

where k is the number of subgroups or observations and $|X_i-\bar{X}|$ is the a solute difference between the average discharge rate $\bar{X}$ and the i-th value X_i.

EU = Emission uniformity of Karmeli and Keller (2): $100\ q_n/q_a$, where q_n is the average discharge rate for the lowest one-fourth of flowing emitters, and q_a the overall average discharge rate.

EU_a = Absolute emission uniformity of Karmeli and Keller (2): $(100/2)(q_n/q_a + q_a/q_x)$, where q_x is the average discharge rate for the highest one-eighth of flowing emitters.

$\bar{X}_{Avg}$ = Overall average discharge rate of emitters.

$\bar{X}_{25}$ = Average discharge rate for lowest one-fourth of flowing emitters.

$\bar{X}_{12.5}$ = Average discharge rate for highest one-eighth of flowing emitters.

CV_i = Coefficient of variation, initial or manufacturers' value.

CV_f = Coefficient of variation, final or computed value.

Table 1: Descriptions of Water Treatment and Emitter Types

Water Treatment

A. Screen filtration (50-mesh) on day 258 (40-mesh previously)
B. Screen filtration (50-mesh) on day 258 + intermittent hypochlorite-acid on day 278 (200-mesh only previously)
C. Sand followed by screen (200-mesh) filtration
D. Treatment C + intermittent hypochlorite-acid
E. Treatment C + continuous hypochlorite-acid
F. Treatment C + continuous acid

Emitter Type

1. Long-path, capillary
2. Long-path, spiral-grooved, manual-flush
3. Long-path, spiral-grooved, manual-flush
4. Automatic, diaphragm, orifice-plate
5. Short-path, removable, spiral-grooved insert
6. Automatic, needle-flush
7. Automatic, ball-flush
8. Single vortex

Table 2. Complete clogging, percent; [average discharge rate, gph]; and (coefficient of variation, CV) for various emitter-water treatment combinations.

WATER TREATMENT

Emitter Number	A	B	C**	D	E	F
1* [1.67] (0.06)	--	--	29.0 [0.86] (0.68)	10.7 [1.20] (0.46)	21.4 [1.00] (0.65)	15.4 [1.41] (0.58)
2 [1.98] (0.06)	0 [1.50] (0.19)	0 [1.51] (0.20)	0 [1.10] (0.40)	0 [1.32] (0.31)	0 [1.44] (0.27)	0 [1.63] (0.15)
3 [1.00] (0.08)	10.0 [0.65] (0.38)	0 [0.68] (0.35)	13.0 [0.55] (0.54)	6.5 [0.51] (0.51)	0 [0.66] (0.29)	0 [0.78] (0.16)
4 [0.93] (0.10)	0 [1.66] (0.34)	2.2 [0.23] (0.38)	0 [1.55] (0.60)	0 [0.43] (0.50)	0 [0.34] (0.27)	0 [1.05] (0.19)
5 [1.45] (0.20)	--	--	11.1 [0.92] (0.59)	0 [1.22] (0.87)	5.6 [1.13] (0.42)	11.1 [0.89] (0.62)
6 [1.02] (0.10)	-- --	-- --	12.5 [0.95] (0.55)	0 [1.33] (0.30)	6.2 [0.98] (0.77)	8.3 [0.96] (0.62)
7 [1.28] (0.17)	-- --	-- --	0 [0.88] (0.18)	0 [1.39] (0.53)	0 [1.03] (0.29)	0 [1.03] (0.14)
8 [1.07] (0.20)	--	--	27.9 [0.71] (0.68)	22.7 [0.73] (0.64)	11.4 [0.89] (0.41)	9.1 [0.99] (0.34)

*
Initial measurement in column 1, Average discharge rate value in brakets, [ ], and coefficient of variation in parenthesis, ( ).

**
Clogging and CV for 1C, 2C, 3C, and 4C estimated from 1978 data.

Table 3. Causes of clogging or flow reduction and relative percent occurrence in trickle irrigation emitter. 1/

Causes of Clogging	Percent of Occurrence: Individual	Percent of Occurrence: Total
Physical Factors:		
Sand Grain	17	
Plastic Particles	26	
Sediment	2	
Body Parts of Insects & Animals	3	
Deformed Septa[2]	7	55
Biological Factors:		
Microbial Slime	11	
Plant Roots & Algal Mats	3	14
Chemical Factors:		
Carbonate Precipitates	2	
Iron-Magnesium Precipitates	0	2
Combined Factors:[3]		
Physical/Biological	8	
Physical/Chemical	2	
Chemical/Biological	6	
Physical/Biological/Chemical	2	18
Non-Detectable (Probably Physical)	--	11

1. Results are representative of 8 emitter systems and four water treatments (C, D, E, and F), that were operated for more than four years. There were 1200 emitters installed in these water treatments and 119 with reduced flow or clogged conditions (<50%) design flow) were dissected and microscopically examined for causes of flow reductions.

2. Rubber septa in emitter types, 6 were deformed by water treated with chlorine and acid (Treatments D and E), which restricted flow.

3. The observations indicated that the most likely initial cause of flow reduction was a physical factor, followed by the development of biological and chemical factors. The major physical factors involved were sand grains and plastic particles.

Table 4. Major genera of bacteria and their occurrence in water and sediments in representative samples of six water treatments and eight emitter types after four years of operation.

	Water			Sediment		Biologically clogged emitters	Totals	Percent
	CRW	Emitter	Submain	Emitter	Lateral			
Pseudomonas stutzeri	2	13	6	18	18	8	65	76
Flavobacterium lutescens	–	7	1	10	4	2	24	28
Vibrio sp.	–	5	1	6	6	2	20	23
Micrococcus sp.	–	3	3	1	7	2	16	19
Bacillus sp.	–	2	1	5	4	1	13	15
Flavobacterium aquatile	2	4	1	1	2	1	11	12
Brevibacterium linins	–	1	–	2	1	3	7	8

TABLE 5. Computed parameters related to uniformity for different degrees of clogging at CV_i = 0.05

	1 Emitter/Plant					2 Emitters/Plant				
Clogging %	$\overline{X}$ Vol./hr	UC_c %	EU %	EU_a %	CV_f	$\overline{X}$ Vol./hr	UC_c %	EU %	EU_a %	CV_f
0	1.00	95.7	93.1	92.5	0.05	2.00	96.9	94.9	94.6	0.04
1	0.99	94.6	90.2	90.6	0.11	1.98	95.8	92.0	92.7	0.08
5	0.95	89.0	78.1	82.8	0.24	1.90	90.1	80.6	85.2	0.16
10	0.90	80.1	61.4	72.1	0.34	1.80	81.8	64.3	74.6	0.24
20	0.80	60.7	22.6	48.2	0.50	1.60	67.8	51.6	63.7	0.35
30	---	---	---	---	---	1.40	55.4	44.5	55.9	0.46

	4 Emitters/plant					8 Emitters/plant				
Clogging %	$\overline{X}$ Vol./hr	UC %	EU %	EU_a %	CV_f	$\overline{X}$ Vol./hr	UC %	EU %	EU_f %	CV_f
0	4.00	97.9	96.7	96.2	0.03	8.00	98.6	99.3	98.1	0.02
1	3.96	96.9	94.0	94.4	0.06	7.92	97.5	96.7	96.4	0.04
5	3.80	91.3	82.8	87.0	0.12	7.60	93.0	89.8	91.2	0.08
10	3.60	85.5	76.2	81.4	0.17	7.20	91.2	86.8	87.6	0.11
20	3.20	79.6	66.6	72.1	0.25	6.40	84.9	77.3	78.1	0.18
30	2.80	73.5	57.6	63.1	0.33	5.60	79.5	69.5	71.4	0.23

TABLE 6. Computed parameters related to uniformity for different degrees of clogging at $CV_i = 0.10$

	1 Emitter/Plant					2 Emitters/Plant				
Clogging %	$\overline{X}$ Vol./hr	UC_c %	EU %	EU_a %	CV_f	$\overline{X}$ Vol./hr	UC_c %	EU %	EU_a %	CV_f
0	1.00	91.4	86.2	85.6	0.10	2.00	93.8	89.8	89.5	0.08
1	0.99	90.4	83.5	83.8	0.15	1.98	92.7	87.1	87.7	0.11
5	0.95	85.6	71.8	76.4	0.25	1.90	87.7	76.7	80.9	0.18
10	0.90	77.9	55.8	66.3	0.35	1.80	81.3	62.0	71.2	0.25
20	0.80	59.7	19.4	44.0	0.51	1.60	68.5	49.6	60.9	0.36
30	---	---	---	---	---	1.40	58.8	42.3	53.4	0.41

	4 Emitters/Plant					8 Emitters/Plant				
Clogging %	$\overline{X}$ Vol./hr	UC %	EU %	EU_a %	CV_f	$\overline{X}$ Vol./hr	UC %	EU %	EU_f %	CV_f
0	4.00	95.8	93.4	92.7	0.05	8.00	97.1	95.4	94.7	0.04
1	3.96	94.9	90.9	91.0	0.07	7.92	96.2	93.1	93.2	0.05
5	3.80	90.5	81.2	84.4	0.13	7.60	92.7	87.3	88.8	0.09
10	3.60	85.5	75.1	79.3	0.17	7.20	90.5	83.9	85.4	0.12
20	3.20	79.4	65.3	70.4	0.25	6.40	84.4	74.8	76.4	0.19
30	2.80	73.1	56.3	61.8	0.34	5.60	80.2	67.5	70.2	0.24

TABLE 7. Comparison of discharge rates for various combinations of clogging and emitters per plant emitters (CV_i = 0.05, discharge = Vol./hr.)

	1 Emitter/Plant			2 Emitters/plant		
Clogging %	$\bar{X}_{25}$	$\bar{X}_{avg}$	$\bar{X}_{12.5}$	$\bar{X}_{25}$	$\bar{X}_{avg}$	$\bar{X}_{12.5}$
0	0.93	1.00	1.09	1.90	2.00	2.12
1	0.89	0.98	1.09	1.82	1.98	2.12
5	0.74	0.95	1.09	1.53	1.90	2.12
10	0.55	0.90	1.09	1.16	1.80	2.12
20	0.18	0.80	1.08	0.82	1.60	2.11
30	--	--	--	0.63	1.40	2.09

	4 Emitter/Plant			8 Emitter/Plant		
Clogging %	$\bar{X}_{25}$	$\bar{X}_{avg}$	$\bar{X}_{12.5}$	$\bar{X}_{25}$	$\bar{X}_{avg}$	$\bar{X}_{12.5}$
0	3.87	4.00	4.19	7.94	8.00	8.25
1	3.72	3.96	4.18	7.65	7.92	8.24
5	3.15	3.80	4.17	6.83	7.62	8.21
10	2.74	3.60	4.15	6.25	7.20	8.14
20	2.13	3.20	4.12	4.94	6.40	8.10
30	1.61	2.80	4.08	3.89	5.60	7.64

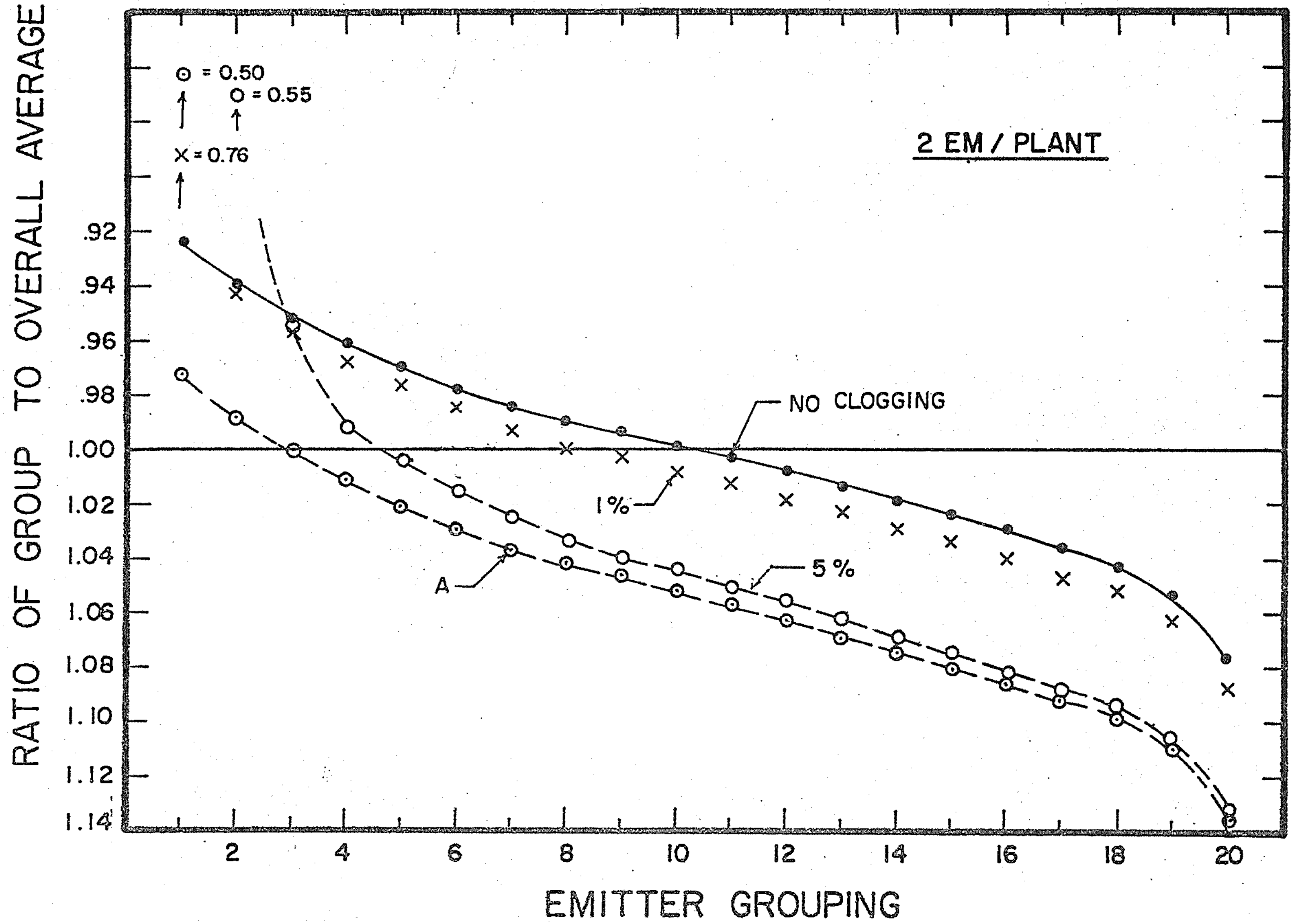


Figure 1. Effect of clogging on the average discharge rate distribution - 2 emitters per plant Curve A represents irrigation based on $\bar{X}_{25}$.

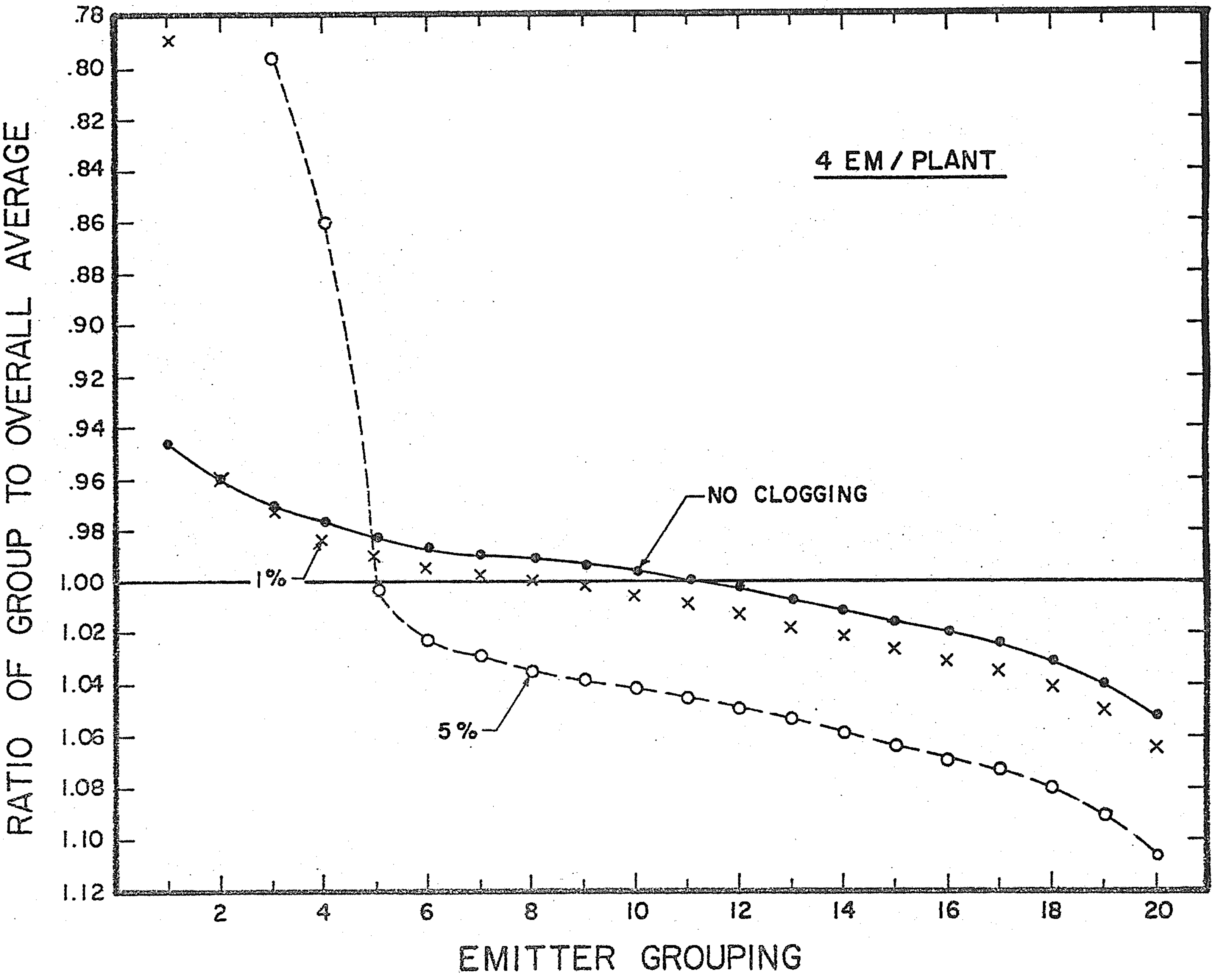


Figure 2. Effect of clogging on the average discharge rate distribution - 4 emitters per plant.

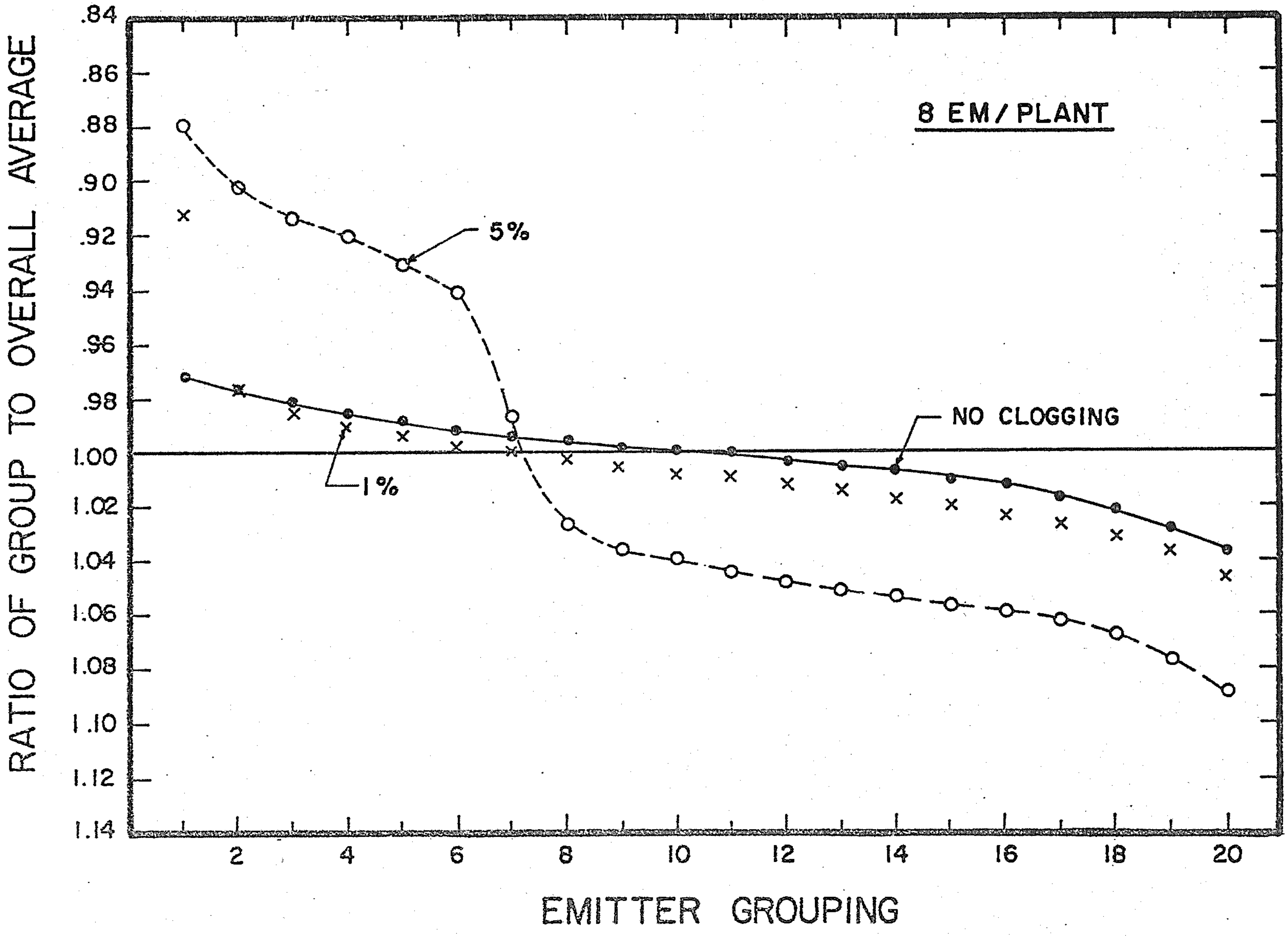


Figure 3. Effect of clogging in the average discharge rate distribution - 8 emitters per plant.

TITLE: WATER-USE BEHAVIOR OF TWO COTTON SPECIES

NRP: 20760 CRIS WORK UNIT 5510-20760-001

INTRODUCTION:

Water-use efficiency, i.e., the yield of cotton lint per unit of applied water, has long been used for comparing the productivity of different cotton cultivars grown under various irrigation management schemes. In the past, growers have usually applied more water to the Pima cottons (*Gossypium barbadense* L.) than to Upland cotton varieties (*G. hirsutum* L.) in the belief that the former had a lower water-use efficiency. Recently, however, lint yield data collected by Kittock (2) indicated that both varieties respond the same to irrigation scheduling. As a consequence, similar irrigation management techniques are now being used for Pima and Upland cotton. The purpose of the present report is to document the water-use characteristics of both varieties as measured through an analysis of soil moisture depletion observations.

PROCEDURE:

Detailed descriptions of the experimental design were reported earlier by Kittock (2). Briefly, the irrigation schedules consisted of altering the frequency, but not the overall seasonal amount of applied water. The treatments which we called "wet", "medium", and "dry" were irrigated at 7, 14 and 21 day intervals, respectively. In 1975 and 1977, we planted the long-staple 'Pima S-5' cultivar; the upland short-staple variety 'Deltapine-16' in 1975, and 'Deltapine-16' in 1977. Water used by the two cultivers within the same whole irrigated plot was determined from water content changes in the top 150 cm soil profile. Two replications were included in each treatment. Volumetric water content was measured at 20-cm intervals with a neutron scattering technique (3). The amount of water from the surface to a depth of 10 cm was estimated from a previously determined calibration relating it to the moisture content at the shallowest 20-cm depth (Nakayama, unpublished data). Soil moisture measurements were made at 2- to 3-day intervals beginning in May and continuing through October (ca. 6 weeks after the last irrigation) for both years.

RESULTS AND DISCUSSION:

Water use, defined as the change in soil water content between two successive measurement dates, relates directly to evapotranspiration or consumptive use. Our data indicated that soil water content at the 160 cm depth remained below field capacity and thus losses to deep percolation could be ignored for the purpose of comparing varieties.

The mean daily water uses for plants in each treatment are presented in Figure 1 for Pima cotton and Figure 2 for Deltapine cotton in 1975.

Similar results were obtained for the 1977 experiment and hence are not shown here. It is significant to note that our data obtained by the neutron scattering technique confirm the gravimetrically estimated seasonal consumptive use by Erie et. al. (1) for 'Acala' and 'Deltapine' varieties of cotton in the same geographical region. Their data are shown as circled "X's" superimposed upon the 'Acala' and 'Deltapine' varieties of cotton in the same geographical region. Their data are shown as circled "X's" superimposed upon the "dry" treatment in Figures 1 and 2.

Unreasonably large water use was evident when computed from the neutron-estimated moisture content immediately following an irrigation (circled-dot symbols). We believe this to be caused by a high rate of evaporation from the water surface and wet soil and not typically representative of the actual consumptive use by the plants. Those values were omitted when calculating the season-long water use. These estimated water-use values for the "dry", "medium", and "wet" treatments were 103, 112, and 130 cm of water, respectively, for the 'Pima' and 103, 105, and 120 cm for the 'Deltapine' variety. The consumptive use in both the dry and medium treatments is close to the 9 year average of 105 cm per season estimated by Erie et al. (1) using gravimetric sampling. The calculated water-use in the wet treatments was substantially higher than this, however. This was attributed to higher evaporation from the continually wet soil surfaces as well as greater vegetative growth in those treatments.

In Figure 3, the ratio of water use of Pima cotton to that of Deltapine for the "dry" treatment as a function of time is compared. A ratio of one indicates identical water use behavior by both varieties. Any long term deviation from one would imply differential use for that period of time. Although very early and late in the season, Deltapine cotton appeared to have had a higher consumptive rate, the data are misleading because the actual water-use values were very small. The ratio remained near the value of 1.0 indicating that both cultivars responded similarly to the dry treatment during most of the growing season. Ratios were 0.9 and 1 for the "medium" and "wet" treatments, respectively.

Although the Pima cultivar used about 8% more water during the entire season than Deltapine when grown under the medium and wet irrigation treatments, there did not appear to be any period during the growing cycle where the consumptive use was markedly different. Thus our results indicate the season-long use of water by these two varieties is similar and support the lint yield data of Kittock which show both varieties can be managed by similar irrigation techniques.

SUMMARY AND CONCLUSIONS:

Water use behavior of two cotton cultivars 'Pima' and 'Deltapine' were found to be similar and could be managed by similar irrigation management schemes. The neutron moisture measurement method used to obtain the water use data supports earlier work of Erie and co-workers where consumptive use was determined by the gravimetric sampling procedure.

REFERENCES:

1. Erie, L. J., O. F. French, and K. Harris. 1976. Consumptive use of water by crops in Arizona. University of Arizona Tech. Bull. 169.

2. Kittock, D. L. 1979. Pima and upland cotton response to irrigation management. Agron. J. 71:617-619.

3. Van Bavel, C. H. M., P. R. Nixon, and V. L. Hauser 1963. Soil moisture measurement with the neutron method. USDA, ARS-41-70.

PERSONNEL: F. S. Nakayama, P. J. Pinter, Jr. and D. L. Kittock, (Cooperator)

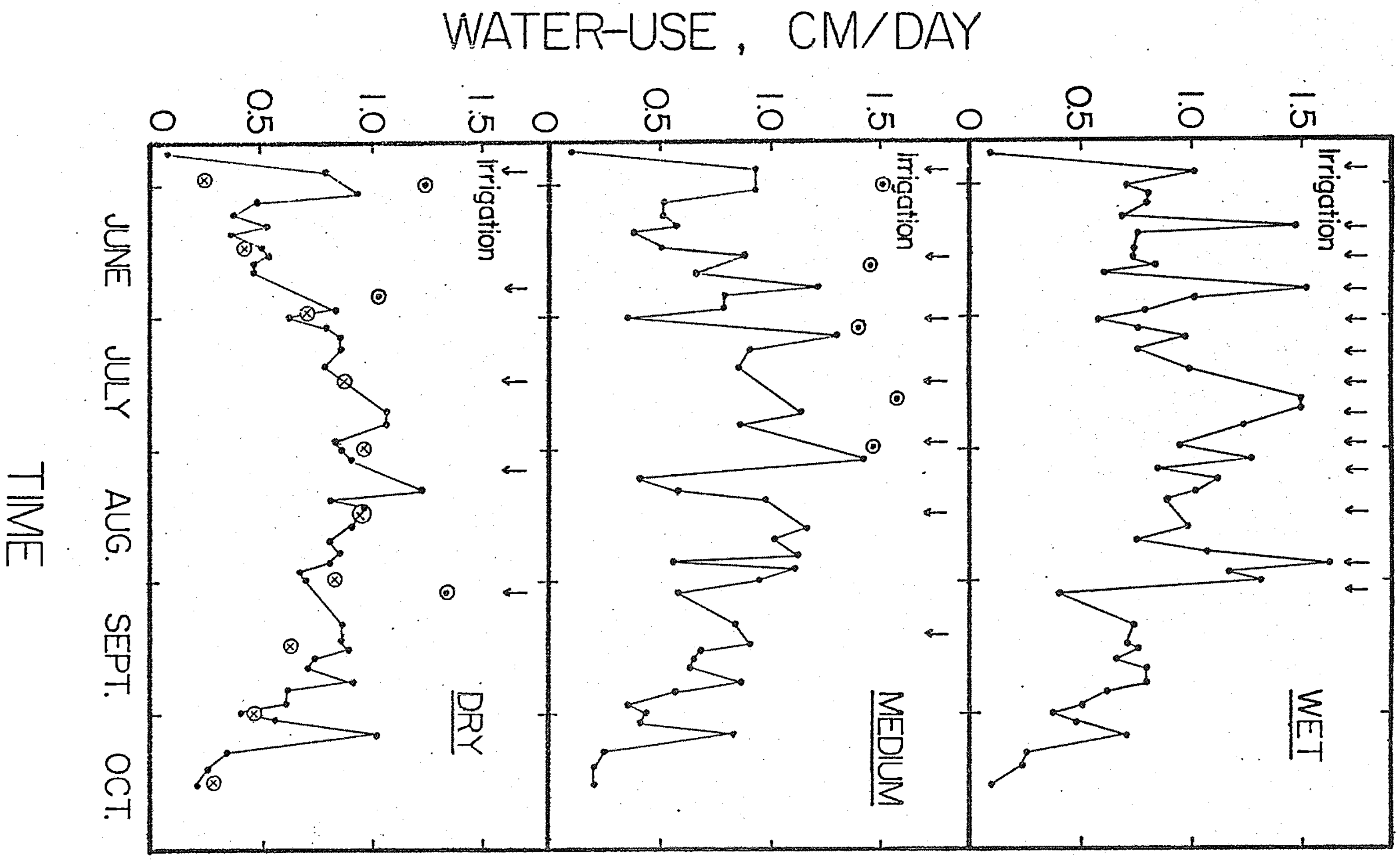


Figure 1. Water-use relations for the 'Pima' cultivar at three irrigation schedules. (Arrows indicate irrigation date).

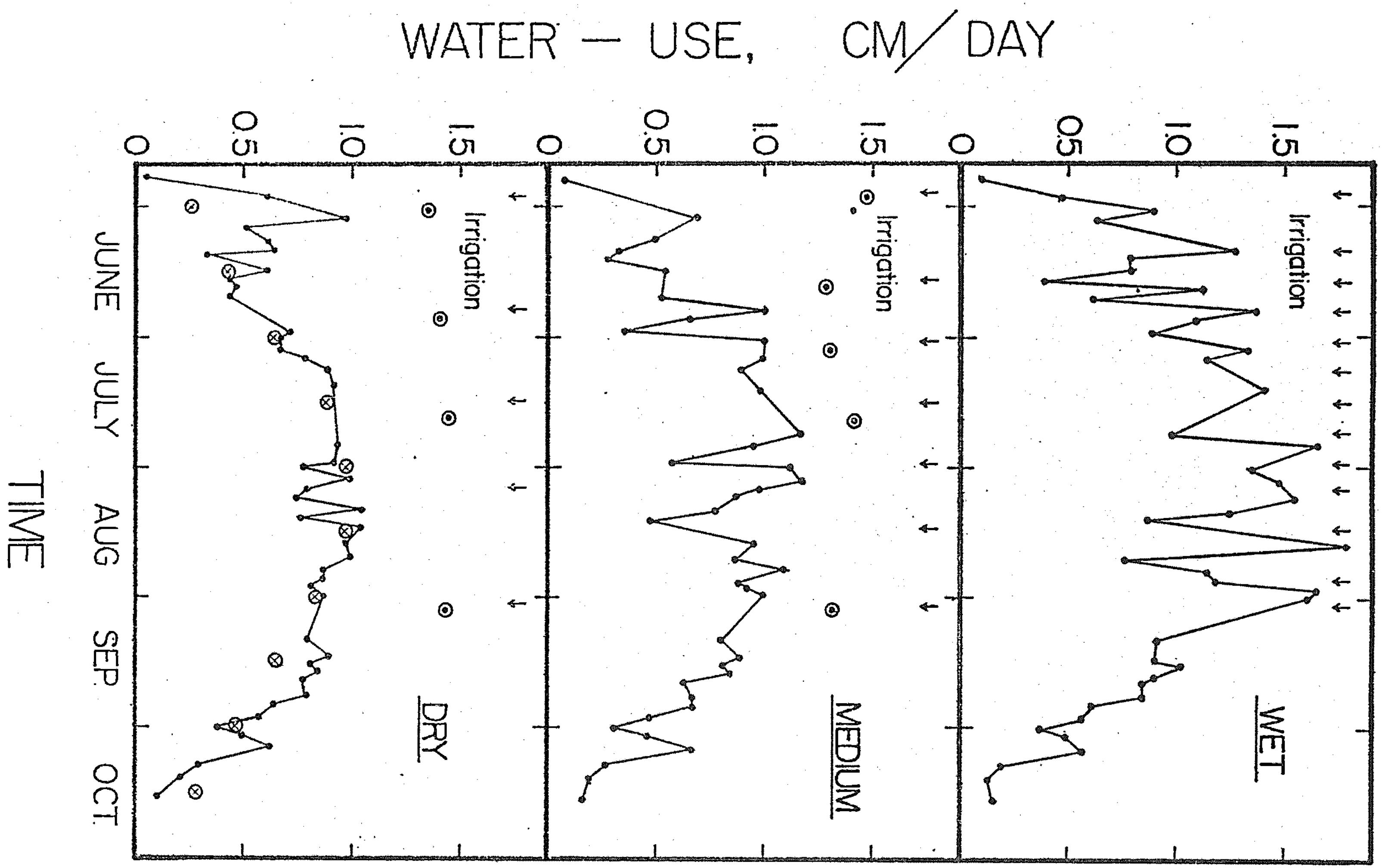


Figure 2. Water-use relations for the 'Deltapine' cultivar at three irrigation schedules. (Arrows indicate irrigation date).

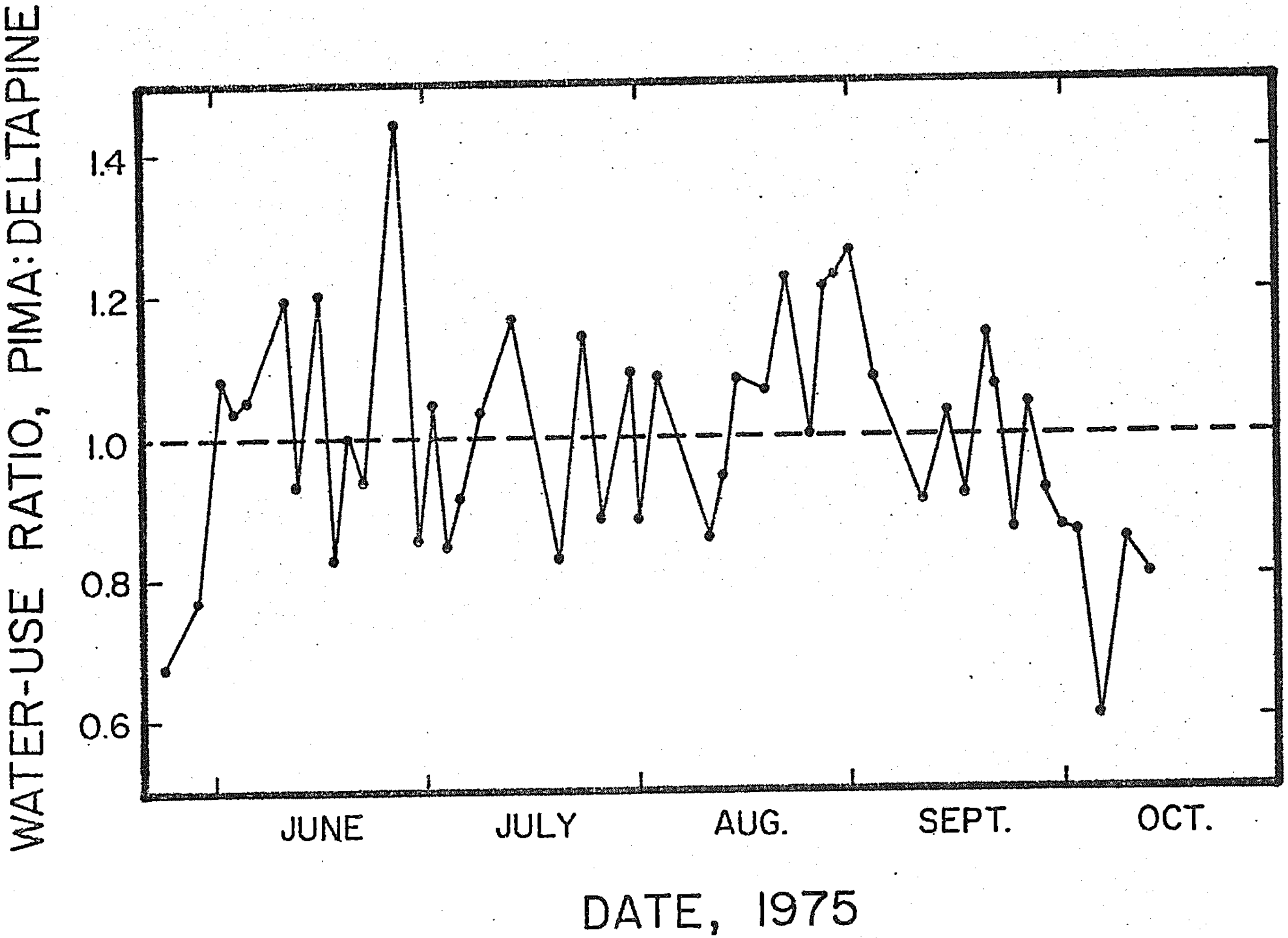


Figure 3. Ratios of water-use with time between the 'Pima' and 'Deltapine' cultivars.

TITLE: SIMPLIFYING NEUTRON MOISTURE METER CALIBRATION

NRP: 20760 CRIS WORK UNIT 5510-20760-001

INTRODUCTION:

The ability to transfer calibration curves directly from one neutron moisture meter (NMM) system to another can greatly simplify probe calibration and thus improve the reliability of field measurements. Purchasers of moisture probes may rely entirely on seller-supplied calibration curves that may not be applicable to the conditions for which the instrument is being used. To circumvent this possible problem, ideally, what is needed is one master reference NMM system that has been field calibrated and against which all other NMM's could be laboratory calibrated. This would be well suited for organizations that use several meters, and particularly for manufacturers of the equipment who need to supply the NMM calibration curves.

At present, direct instrument calibration is a tedious task. In the laboratory, a common procedure is to pack soil at a specific water content and bulk density around the access tube and to measure the resultant thermalized neutron flux. This procedure is repeated for several water contents, and a calibration curve derived from the volumetric water content-count rate relationship. In the field, the soils may be sampled from around the access tube for volumetric water content determination after the NMM measurements or prior to these measurements by sampling the core from which the access tube is inserted. This procedure must be repeated over a range of soil water contents to obtain the NMM calibration curve. Because of soil disturbance during sampling, the same site cannot be reused.

PROCEDURE:

A description of the four neutron moisture meters used, including source strength, probe model, reference absorber for obtaining relative count ratios, R_c, and scaler is listed in Table 1. The diameter for the two different types of probes is approximately 4.77 cm (1.877 in.). The Am-Be source is located at the bottom of the probe just under the detector tube.

The NMM's were field calibrated in an Avondale clay loam soil. Steel (5.258 ID x 0.165 cm wall thickness; 2.070 x 0.065 in.) and aluminum (4.826ID x 0.124 cm wall thickness; 1.90 x 0.049 in.) access tubes were installed to a depth of 100cm in separate 1.8 x 1.8 meter (5.9 x 5.9 ft) plots. A berm surrounded the plots so that water could be added for moisture adjustments prior to the measurements. All four NMM's were used in each access tube before the soil was sampled. Four replicated readings per probe were taken at 20 cm depth increments to

80 cm maximum depth. Replicated 30 seconds standard counts were also taken for every probe in its own reference absorber shield. Duplicate soil samples were taken 5 cm from the access tube with 5.50 cm (2.16 in.) diameter by 3.00 cm (1.18 in.) high rings fitted into a core sampler. Construction details of the soil sampler and core retainer are presented elsewhere (1). After each sampling, the remaining soil around the access tube was cleared and leveled for the next sample increment. Volumetric water contents θ_v and bulk densities were determined from these samples. The volumetric water contents were related to R_c, the ratio of count rate in soil to the count rate in the standard reference absorber for the particular NMM system to obtain the calibration curves for each of the the four NMM's.

Count rates for the four NMM's were also taken in low-density polyethylene plastic cylinders of varying absorber thicknesses. The probes snugly fitted in the 4.84 cm (1.907 in.) diameter cavity drilled into 7.62, 8.89, 10.16 and 11.43 cm (3.0, 3.5, 4.0, and 4.5 in.) outside diameter by 46 cm (18.124 in.) long cylinders. For this plastic system, R_c was related to the absorber thickness, which was the total cylinder diameter minus the cavity diameter.

RESULTS AND DISCUSSION:

The regression equations relating volumetric water contents for various NMM's in aluminum or steel access tubing to the count rate ratios, and equation relating plastic cylinder diameter to R_c are presented in Table 2. In all cases the linear relation was good with correlation coefficient in the 0.98 range and better. Different relations were obtained using the aluminum and steel access tubes so that direct transference of the calibration curves from one type of tubing to another cannot be made. The results also indicate that if one NMM system is used as a standard (having been previously calibrated in the field or other type of soil media), other NMM systems can be calibrated against it without going through the tedious task of taking the basic calibration samplings for bulk density and volumetric water contents. The procedure to follow in this case would be to determine R_c's for the probe to be calibrated and for the standard probe in the same access hole at approximately the same time. Then the regression equation determined from the measured R_c, and the calculated θ_v from the regression equation for the standard NMM system. For example, when this procedure was followed using the Campbell probe as the standard, the resultant regression equations for the remaining three probes in the aluminum access tube were as follows:

$$\text{Troxler (23653)} = -0.0745 + 0.500\,R_c,\ (r^2 = 0.997)$$
$$\text{Troxler (904)} = -0.0936 + 0.483\,R_c,\ (r^2 = 0.997)$$
$$\text{Troxler (C-3496)} = -0.0884 + 0.405\,R_c,\ (r^2 = 0.998)$$

These equations compare favorably with those derived on basis of the originally measured volumetric water content of Table 2.

The slopes and intercepts of the aluminum-steel and aluminum-plastic combinations were also compared (Figure 1 & 2) to see whether a method can be developed for transferring calibration curve from one type of calibrated system to another. With the aluminum-steel system the slopes relation is very good ($r^2 = 0.994$) so that it would be possible to estimate the slope for one system if the other is known. In this case the equation for estimating the slope factor in steel (S_{st}) from aluminum (S_{al}) is $S_{st} = - 0.0402 + 1.262\ S_{al}$). The intercept relation for the steel (I_{st}) and aluminum (I_{al}) is $I_{st} = 0.00128 + 1.090\ (I_{al})$. The absolute water content estimated from such a derived regression, using S_{st} & I_{st} for example, would have a greater error than that for the differences in changes in water contents with time since the intercept factor would cancel out in the calculation process.

The estimated regression equations for the various NMM's transferring calibration from an aluminum to steel access tubing are as follows:

SYSTEM	ESTIMATED REGRESSION EQUATION
A.	$\theta_v = - 0.0895 + 0.614\ R_c$, (steel)
B.	$\theta_v = - 0.0746 + 0.341\ R_c$, (steel)
C.	$\theta_v = - 0.1022 + 0.571\ R_c$, (steel)
D.	$\theta_v = - 0.0960 + 0.472\ R_c$, (steel)

Comparison of these to the equations of Table 2 for the calibration of the NMM's in steel tubing show good agreement between these two methods for obtaining the regression equation.

The slope-intercept relation between the plastic absorber and the soil absorber with aluminum access tubing is also good. In this case $S_{al} = 0.0542 + 0.0801\ S_{pl}$ ($r^2 = 0.884$) and $I_{al} = 0.0555 - 0.0832\ I_{pl}$ ($r^2 = 0.965$) can be used to get the regression equation of a probe for this particular soil type if the relations have been previously established between the plastic and soil absorbers. When these S_{al} and I_{al} are used to estimate the regression equation, the following are obtained.

SYSTEM	ESTIMATED REGRESSION EQUATION
A.	$\theta_v = - 0.0804 + 0.476\ R_c$, (aluminum)
B.	$\theta_v = - 0.0713 + 0.296\ R_c$, (aluminum)
C.	$\theta_v = - 0.0960 + 0.496\ R_c$, (aluminum)
D.	$\theta_v = - 0.0892 + 0.441\ R_c$, (aluminum)

These estimated equations compare favorably with those in Table 2 derived originally from experimental field data using the aluminum access tubing.

SUMMARY & CONCULSIONS:

Neutron moisture meter (NMM) calibration can be greatly simplified by developing and using the relationship between neutron thermalization in soil and another moderator such as plastic. The procedure requires several NMM's initially to establish the interrelation between the slope and intercepts from the various regression equations of the meters in different materials. This method of calibration could be handy for NMM manufacturers and organizations that use several NMM systems.

Where equipment is limited, one reference NMM can be calibrated separately and other NMM's calibrated against it by comparing readings at the same site and relying on the estimated volumetric water content from the standard probe for developing the regression equation for the new or uncalibrated probe.

PUBLICATIONS:

1. Richards, L. A. (ed.) Diagnosis and improvement of saline and alkaline soils. USDA Agric. Handbook 60. 1954.

PERSONNEL: F. S. Nakayama, R. J. Reginato, B. A. Rasnick, and R. S. Seay.

Table 1. Description of Neutron Moisture Meter Systems

	MANUFACTURER			
	CAMPBELL	TROXLER	TROXLER	TROXLER
SOURCE STRENGTH				
mCi	50	100	100	150
Serial No.	---	AM7068	AM7022	50AM134
PROBE MODEL	503	104A	104A	104A
Serial No.	H3903264	C-3496	0904	23653
ABSORBER-SHIELD				
Type	Paraffin	Plastic	Water	Water
Model No.	H39032648	1255	VMP-487	VMP-487
SCALER MODEL	503	2601	2651	600

Table 2. Regression Equations relating volumetric water content (θ_v) or plastic cylinder thickness (T) to count ratio.

PROBE	COMPUTED REGRESSION EQUATION
A. Troxler, #23653	$\theta_v = -0.0832 + 0.518 R_c$ (Aluminum), $r^2 = 0.993$
	$\theta_v = -0.0930 + 0.609 R_c$ (Steel), $r^2 = 0.987$
	$T = 1.633 + 5.266 R_c$ (Plastic), $r^2 = 0.998$
B. Cambell, #H3903264	$\theta_v = -0.0696 + 0.302 R_c$ (Aluminum), $r^2 = 0.990$
	$\theta_v = -0.0752 + 0.344 R_c$ (Steel), $r^2 = 0.982$
	$T = 1.524 + 3.022 R_c$ (Plastic), $r^2 = 0.992$
C. Troxler, #904	$\theta_v = -0.0950 + 0.484 R_c$ (Aluminum), $r^2 = 0.993$
	$\theta_v = -0.1081 + 0.582 R_c$ (Steel), $r^2 = 0.987$
	$T = 1.821 + 5.519 R_c$ (Plastic), $r^2 = 0.999$
D. Troxler, #C-3496	$\theta_v = -0.0892 + 0.406 R_c$ (Aluminum), $r^2 = 0.994$
	$\theta_v = -0.0860 + 0.462 R_c$ (Steel), $r^2 = 0.981$
	$T = 1.737 + 4.830 R_c$ (Plastic), $r^2 = 0.999$

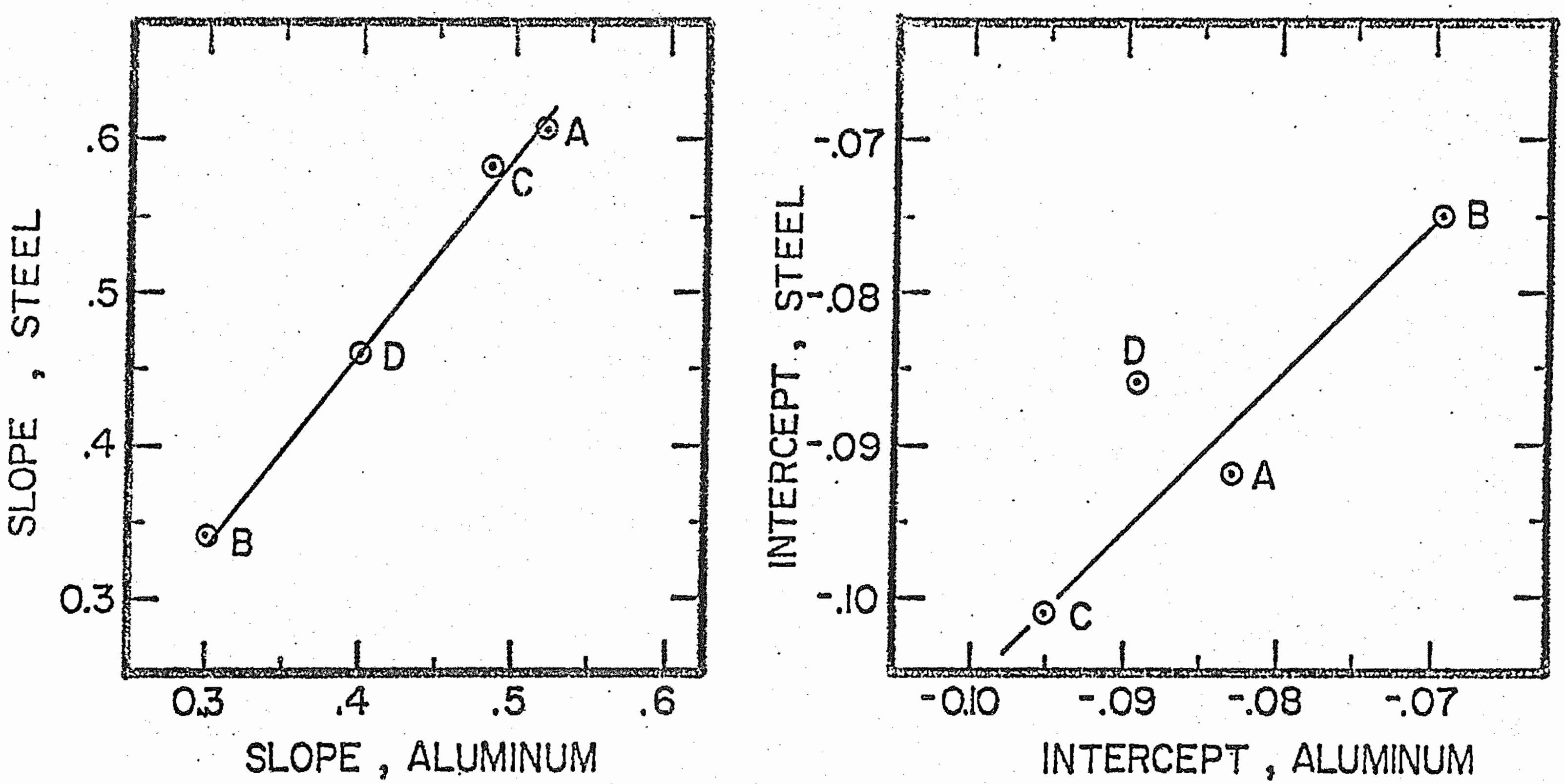


Figure 1. Slope and intercept relations from regression equations obtained for steel and aluminum access tubing with the different NMM systems.

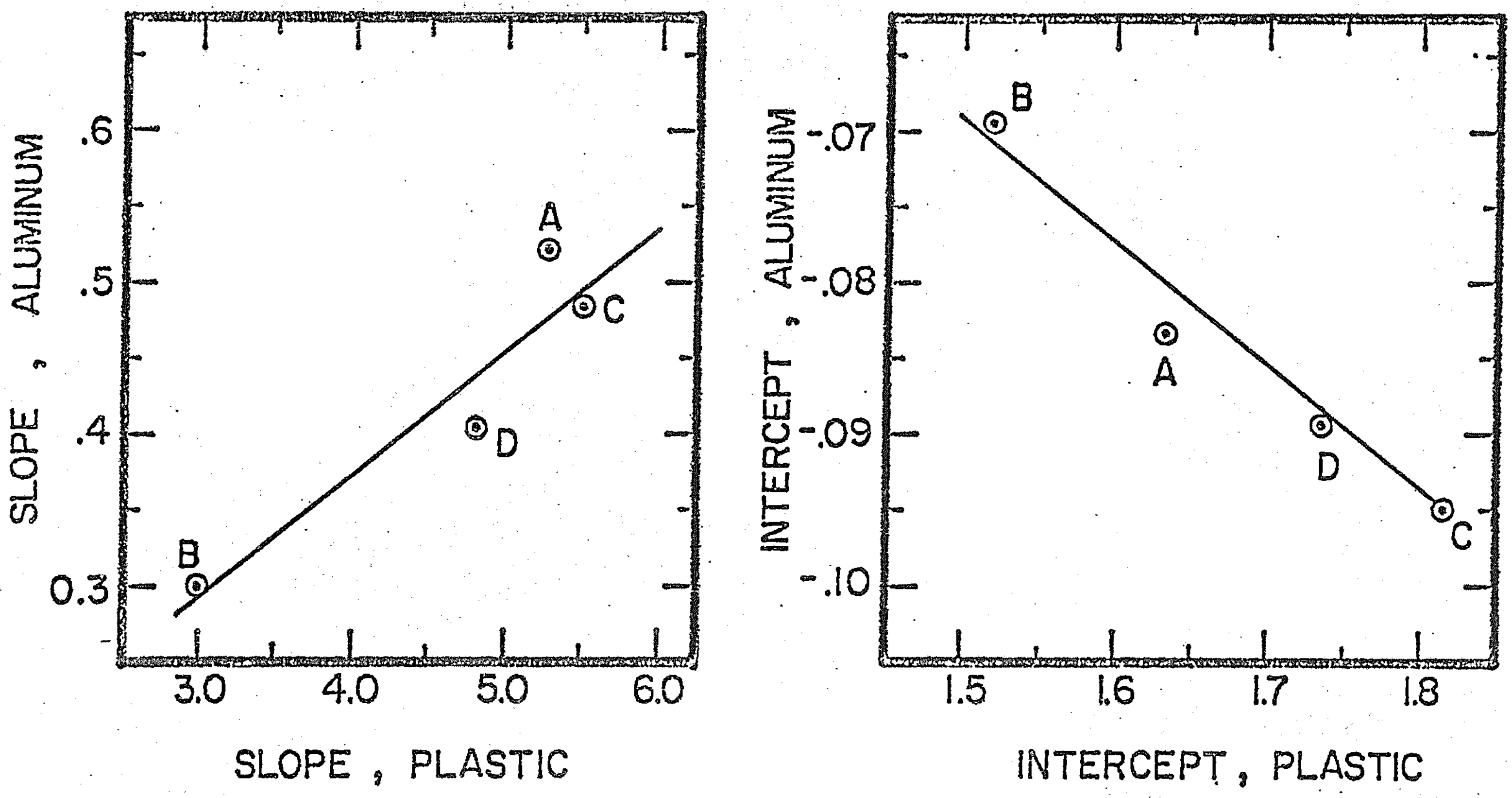


Figure 2. Slope and intercept relations from regression equations obtained for aluminum access tubing and plastic absorber with the different NMM systems.

TITLE: MATHEMATICAL MODELING OF BORDER IRRIGATION HYDRAULICS

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

INTRODUCTION:

Surface irrigation is an extremely complex phenomenon. The flow of water in an irrigation border can be described as unsteady and gradually varied. The resistance to flow varies spatially over the field and can even change as the water flows past. Variations in field slope (and sometimes sideslopes) cause an additional complication. However, adequately determining the infiltration characteristics of a soil is by far the biggest stumbling block in accurately describing and/or predicting the irrigation process. Theoretical infiltration formulas are of little usefulness because they inadequately describe the conditions of the soil surface which tend to dominate infiltration in surface irrigation. These surface conditions often change drastically from irrigation to irrigation due to a variety of factors. Thus, empirical methods are most often used in the field. This paper will discuss several imperical methods for estimating infiltration and how these apply to surface irrigation.

INFILTRATION THEORY

The theory of infiltration into soils has changed considerably over the last few decades. The most significant advancement in the science of infiltration has been the change from empirical measurement of the coefficients in the infiltration equations to measurement of physical properties used to derive the infiltration. Although the earlier empirical equations were usually physically based, they failed to account for all of the physical laws governing the system. Several of these so called empirical equations are discussed by Dixon, Simanton and Lane (1978). These are the Kostiakov equation $Z = kt^a$, the Philip equation $Z = At^{1/2} + Bt$,the Ostashev equation $Z = At^{1/2}$ and the Darcy equation $Z = At$ where Z is the accumulated depth infiltrated, t is time and k, a, A and B are constants. The last equation is based on Darcy's law for flow through saturated porous media with the area and gradient combined in A. The Ostashev equation is based solely on the spread of water by capillary forces. The Philip equation attempts to combine these two (Philip, 1956) and the Kostiakov equation, for the most part, has no physical intepretation.

These simple equations do not consider the moisture content of the soil and its distribution, the diffusivity of a moving front of infiltrating water, vertical changes in hydraulic conductivity, layering of soils and air pressure buildup in the soil due to a high water table or a layer which restricts air movement. These conditions can all be described by current infiltration theory with the Green-Ampt or Delta-Function model, and similar forms of the piston-flow concept (Philip, 1975). These equations are basically descriptions of Darcy's law which includes capillary forces. These models require detailed information about the properties of the soil and must be solved by numerical methods. The result is not an equation, but a series of points representing infiltrated depth versus time (Whisler and Bouwer, 1970).

Most of the work on theoretical infiltration is done in laboratory columns or other experimental apparatus. Unfortunately, these conditions bear little resemblance to the conditions which occur in an irrigated field. There, infiltration is usually dominated by the conditions which occur at the surface. These surface conditions are effected by tillage operations, wheel traffic, plant growth, biological activities, surface cracking, etc. In laboratory studies, the surface conditions are carefully controlled. It would be virtually impossible to accurately determine the physical parameters necessary for theoretically determining the infiltration in a field situation. Dixon (1974) describes an interesting infiltration concept based on micro- versus macro-pores which attempts to more fully describe field soil infiltration.

INFILTRATION AND SURFACE IRRIGATION

The effects of infiltration on surface irrigation have long been recognized, although probably not thoroughly understood. Bishop (1961) discusses some relationships between infiltration or intake rate and length of run or field length. Christiansen (1966) discusses the relationships between intake and advance of the irrigation stream based on a volume balance. Both analyses make a number of general assumptions about the irrigation process which is considerably different for border and furrow irrigation. Willardson and Bishop extend these concepts to discuss application efficiency. In their analysis they assume constant runoff streams which may be realistic for forrow irrigation, but is not realistic for border irrigation.

The variability in infiltration from irrigation to irrigation, season to season and year to year is well documented in the literature. However, general trends are not evident. Jensen and Sletten (1965) present data on infiltration rates as affected by tillage practices and crops. Linderman and Stegman (1969) discuss the effects of the magnitude of infiltration on application efficiency. They suggest that the maximum attainable efficiencies are not much different, but these maximum efficiencies occur at considerably different flow rates. They did not discuss the effect of the shape of the infiltration curve.

The infiltration properties of a soil are an important part of the design of irrigation borders and basins in the U. S. Soil Conservation Service (SCS) Border Irrigation Handbook (USDA, 1974). Intake families are used to categorize soils for design purposes. These families combine the magnitude and shape of the infiltration function which is of the form $Z = kt^a + c$ where k, a, and c are constants and Z and t were defined earlier. These families are described in terms of infiltration rate, although it appears that there is no consistent relationship between the family name and the associated function. For sloping borders, the design is based on the amount of time water is available for infiltration (opportunity time) at the upstream end of the border. This time must be long enough to infiltrate the required depth of water (referred to as soil moisture deficit, management allowed deficit or net depth of application).

Merriam (1978) has presented a series of infiltration curves similar to the SCS families, except these curves are described by the time necessary to infiltrate 4 inches of water. Also included are two curves which represent infiltration which has very high initial infiltration and very low final infiltration. These two intake function exhibit very sharp curvature. This is an attempt to account for the drastic differences between the SCS families and actual field measured infiltration. These differences are not always attributable to the surface cracking of soils as suggested by Merriam.

RING INFILTRATION MEASUREMENTS

Ring infiltration methods are often used to estimate infiltration in field situations primarily since they are fairly easy to run. As discussed earlier, theoretical approaches are not feasible. The ring infiltration method is often criticized for a number of reasons, however, if properly used, it can provide useful information. Erie (1962) discusses means and methods for properly operating a ring infiltrometer (such as properly seating the rings), as well as some of its drawbacks. Using a buffer area or ring around the infiltration ring or cylinder is unnecessary if the infiltration is measured during an irrigation. Bouwer (1963) discusses the effects of unequal water levels on the infiltration measured in ring infiltrometers and presents an error analysis. Tricker (1978) presents a discussion on the use of infiltration rings without a buffer. He concludes that measured infiltration rates are always higher than what he calls the true infiltration capacity. This tendency does exist when the wetting front goes beyond the end of the ring. However, there are a variety of conditions which cause the measured infiltration to be considerably lower than the actual infiltration. When water is poured into the ring, fine particles are dislodged from the surface and suspended in the water. When these particles settle out, they produce a layer of fine material which tends to reduce infiltration and "seal" the ring. Such a surface does not exist in the border where water is flowing. Flowing water helps to maintain higher infiltration rates. Also, the act of driving the ring tends to compact the soil and cuts off natural paths for air and water flow (macro pores) thus reducing infiltration. For properly seated rings where a buffer is used, measured infiltration will usually be less than the true infiltration.

Power Functions - Methods are necessary to adjust the ring infiltration data to account for the effects of the ring. When the infiltration data is gathered in conjunction with an irrigation, this type of adjustment is possible. Merriam (1971) presented a method for adjusting ring data with opportunity time when fitting the data with a power function. While his method is basically the same as that used here, it lacks any sort of mathematical derivation and explanation. This derivation is necessary in order to expand the method to other functions.

The average depth of infiltration, Z_{BAR} is defined as

$$Z_{BAR} = \frac{\int_o^L Z(x)dx}{\int_o^L dx} \qquad [1]$$

where L is the field length and Z(x) represents the depth infiltrated at distance x from the upstream or head end of the border.

If the field is broken up into N reaches of length Δx_i, equation [1] becomes

$$Z_{BAR} = \frac{\sum_{L=1}^{N} Z(\Delta x_i)\Delta x_i}{L} \qquad [2]$$

if Z(x) is a power function of the form $Z = kt^a$, equation [2] becomes

$$Z_{BAR} = \frac{K}{L} \sum_{i=1}^{N} t_i^a \Delta x_i \qquad [3]$$

where $t_i = t(\Delta x_i)$. For equal increments of Δx, equation [3] becomes

$$Z_{BAR} = \frac{K}{N} \sum_{i=1}^{N} t_i^a \qquad [4]$$

Equation [3] or [4] can be used to estimate the infiltration function with knowledge of the average opportunity time over each distance interval and a value for the shape of the infiltration function, a, from the best fit line for the infiltration data on logrithmic paper. Merriam determines a from the plot of cumulative infiltration versus time. Alternately it could be found from a plot of infiltration rate versus time, where the infiltration rate, $i = akt^{a-1}$. If the infiltration is truly a power function, and cumulative data is recorded accurately from time = 0, then the same value of a should be obtained from either plot. However, it is nearly impossible to obtain precise data from time = 0. This along with experimental errors can result in differences between the two plots.

The results of a number of ring infiltrometer tests are presented in Table 1. The data was obtained from Criddle (1956), Bob Holeman (University of Arizona, Irrigation Extension Specialist, Yuma County, Arizona, unpublished data), Al Dedrick (Agricultural Engineer, U. S. Water Conservation Laboratory, Phoenix, Arizona, unpublished data), and from tests run at the University of Arizona Cotton Research Center, Phoenix, Arizona and at the McDonnell-McElhaney and Wise farms near Wellton, Arizona. The raw data was fed into a computer and a best-fit power function equation was found for both cumulative infiltration and infiltration rate. These constants a presented in columns 3 and 4 and 6 and 7, respectively. Note that in many cases the values of a in columns 3 and 6 are quite different. The differences between values of a ranged from roughly 0.01 to 0.26 with an average of about 0.06. There is a distinct tendency for the a values from the cumulative data to be higher than that for the rate data, particularly from smaller a values. This can be partially explained by the water that infiltrates before the initial reading is taken.

Also presented in Table 1 are the adjusted k values computed from observed opportunity time with equation [3]. Note that good agreement in the shape of the infiltration curve (value of a) between the cumulative and rate data does not correspond to good agreement between measured (best fit) and computed magnitude. The agreement in a values only indicates that this function represents the infiltration within the ring. The important questions to be answered are: When is the ring infiltration data valid? What is the infiltration function when it is valid? What is the infiltration function when the ring data does not agree with the computed volume balance? Consider the ring data from the McDonnell-McElhaney farm (May 26, 1977). Not only are the two a values nearly identical, but the best fit and adjusted k values are also very close. Clearly, the average infiltration function for this irrigation can be adequately described by either adjusted function (i.e., $Z = 2.9t^{0.60}$). On the other hand, the data obtained on the Wise farm (February 20, 1979), is clearly subject to question based on the data presented in Table 1. However, it can be speculated that the two adjusted functions bracket the true infiltration function (data from both clearly followed a power function).

Final Intake -- Another possible explanation for some of these differences is that the infiltration function does not match a power function. The infiltration of water into many soils appears to follow a power function of first, but then begins to deviate and approach a constant value of infiltration rate. This can make a considerable difference in the calculation of subsurface distribution since for a true power function, the infiltration rate approaches zero as time increases and the difference in infiltrated depth over the field becomes less and less. However, if the constant infiltration rate is reach, a uniform increase in opportunity time will not change the differences in infiltrated depth. The constant infiltration rate has a theoretical interpretation. It represents the saturated hydraulic conductivity of the soil or a restricting layer, and is approached as the hydrostatic forces begin to dominate over capillarity and the filling of soil pores.

A number of forms of the infiltration function for a constant final infiltration rate could be used. The easiest mathematically is probably $i = i_f + akt^{a-1}$ and $Z = i_f t + kt^a$. However, it is difficult to obtain values for the three constants i_f (final intake rate), a and k. It is easier to use a two branch function of the form

$$Z = kt^a \qquad t \leq t_f$$
$$Z = kt_f^a + i_f(t - t_f) \qquad t \geq t_f \qquad [5]$$

and

$$i = akt^{a-1} \qquad t \leq t_f$$
$$i = i_f \qquad t \geq t_f \qquad [6]$$

with $i_f = akt_f^{a-1}$ [7]

The final infiltration rate can be determined from a logrithmic plot of infiltration rate versus time. The slope of the initial infiltration can come from either plot, excluding the data points once final intake has been reached. The value for k can be found from a volume balance as before, except once final intake has been reached, only the average opportunity time, t, is needed. The average depth applied is

$$Z_B = k[i_f/ak]^{\frac{a}{a-1}} + i_f \; t_B - [i_f/ak]^{\frac{a}{a-1}} \qquad [8]$$

If we let $C = i_f/a$ and $\phi = Z_B - i_f t_B$ and solve equation [8] for k we get

$$K = {\frac{\phi}{[C]^{\frac{a}{a-1}} - i_f[C]^{\frac{1}{a-1}}}}^{(1-a)} \qquad [9]$$

The variable ϕ represents the difference between the amount of water that was actually applied in the average opportunity time, t_B, and the amount of water that would have been applied if the infiltration rate had been constant at i_f for time t_B. This equation can be solved to determine the magnitude of the initial infiltration. The time t_f can be found from equation [7].

If the volume balance is considerably off, it may not be reasonable to obtain a value for final infiltration rate from the ring data, since surface sealing is likely to have occurred. If we assume that the slope of the infiltration curve before final intake, a, and the time at which final intake begins, t_f, can be obtained from the ring data plots, a volume balance can be used to find i_f from

$$i_f = \frac{aZ_B}{t_f(1-a) + at_B} \qquad [10]$$

which can be developed from equations [5] through [8]. Then k can be found from equation [7].

The ring data taken at the Cotton Research Center (CRC), Phoenix, Arizona, on September 21, 1978, showed a distinct change in infiltration rate after about an hour. A value for i_f was found by averaging the infiltration rates after one hour. The remaining data was fit with a power function as before (both cumulative and rate). A value of t_f was then calculated from equation [7] with the estimated i_f and the best fit a and k. Finally, i_f was calculated from equation [10] and an adjusted k was calculated from equation [7]. These results are given in Table 2, and plotted in Figure 1. (Average of four final intake functions is plotted).

The following is a summary of the steps taken for estimating infiltration from ring infiltration data:

1. Plot data on logrithmic paper - both cumulative and rate versus time.

2. Discard data from obviously bad rings.

3. Find best fit lines through data.

4. Use opportunity time to find adjusted functions with volume balance.

5. Determine an appropriate value for final intake rate.

6. Find best fit lines through data prior to final intake.

7. Use volume balance to determine infiltration function.

8. Plot calculated (adjusted) functions on linear plot and compare.

9. Use judgement to determine which are appropriate.

The results may be somewhat inconclusive, but usually a reasonable estimate of the true infiltration function can be determined from this method.

INFILTRATION FROM BORDER METHODS

Border methods for determining infiltration properties consist of methods which determined both the magnitude and shape of the infiltration function from the observation of water flow over irrigation borders. These methods use a volume balance and either opportunity time differences or measured water depths to determine points along the cumulative infiltration curve. They require accurate knowledge of advance and recession times and border inflow and runoff rates and volumes.

Bouwer's Method -- Bouwer (1957) presented a relatively easy method for estimating infiltration from the observation of a series of irrigations on adjacent borders. The method consists of applying water to several borders at different flow rates and with different volumes of application. This causes variations in opportunity time along each border and between borders. With knowledge of the volume of water applied to each border and values of the average opportunity time for distance increments along each border, the average infiltration rates over several prespecified time intervals can be determined. For practical applications, three (or more) time periods should be specified. The solution technique would then require at least four equations (at least one more equation than unknown), representing data from four irrigation borders. The solution gives a best fit answer for these average infiltration rates.

It should be recognized that the solution techniques used by this method is very general and not specifically developed for this procedure. Thus physical constraints which apply to the infiltration of water into soils are not necessarily taken into account. In the example presented in Bouwer (1957), the average infiltration rate between 1.5 and 3. 5 hours is greater that it was between 0.5 hours and 1.5 hours. While the difference is much smaller than ± one standard deviation, it points to potential problems with the method.

As a test of the general suitability of this procedure, runs from the zero-inertia border irrigation model (Strelkoff, 1979) were used to try this procedure for a known infiltration function. Three runs were made with different flow rates, application times and applied volumes. The particulars are: Manning n = 0.10, bottom slope = 0.001 ft/ft, k = 2.2 in/hr^a, a = 0.21, i_f = 0, field length = 1000 ft, flow rates of 0.0290, 0.06 and 0.0869 cfs/ft, and application times of 210, 137 and 71 minutes for runs 1, 2 and 3, respectively. The results are shown in Fig. 2. Opportunity times ranged from approximately 100 to 300 minutes. Since an exact infiltration function was used, it was unnecessary to have more equations than unknowns. Thus, the three simultaneous equations were solved directly.

The results of Bouwer's method for three sets of time intervals are presented in Table 3. Note the marked tendency for the first and third time periods to over estimate infiltration, while the second under estimates it. The selection of time intervals apparently has an effect on the solution, as does the range in opportunity time. For the example given in Bouwer (1957) the range in opportunity times was 7:1, while here it is only 3:1. Also, that example has time intervals that increase by a factor of two (.5, 1, 2 hours), as do the first two examples in Table 2 (.5, 1, 2, 4 hours respectively). The last example had time periods of 2, 1 and 2 hours, with markedly poorer results.

Bouwer's method was also attempted on data collected from 12 irrigation borders on September 21, 1978. The borders were on three slopes, with three border widths (thus three flow rates) and all within three adjacent fields at the Cotton Research Center, Phoenix, Arizona. Opportunity times ranged from 0 to 208 minutes. The infiltration function determined from the 12 borders with Bouwer's method is plotted in Fig. 1 along with the average adjusted ring data taken on fields 1 and 3. Here, the results look reasonably good. When other combinations of borders were used, the results were terrible. In many cases, the computed value of cumulative depth at three and a half hours (end of last time interval) was negative, with a standard deviation of ten inches or more. One of the difficulties with using this method is variations in infiltration from border to border. This problem is compounded by the difficulty of determining recession times on borders with flat slopes. Obtaining good results with this method requires many replications, fairly uniform soils and accurate data on volumes and opportunity times.

Water Depth Methods -- There are several methods available for estimating infiltration rates when data is available for a single border on advance, recession, inflow rates and volumes, and water depths versus time. Gilley (1968) developed a method for estimating the infiltration function during advance. He assumed a power function advance, a power infiltration function and a constant average surface water depth. The method is only applicable during advance prior to cutoff and generally results in very small infiltration powers. It is not particularly useful for characterizing infiltration for an entire irrigation. Roth (1971) used a trial and error volume balance to determine the infiltration function. This method requires measurements of water depths at a number of stations along the border, while Gilley's method only required the depth at the head end of the field. A more accurate calculation of infiltrated volume is possible when a number of water depths are known. Fangmeier (Roth, et al. 1974) improved upon the trial and error method by using Gilley's method as an approximation of the shape of the infiltration function, then using the actual calculated volume infiltrated to determine a new estimate of infiltrated depths. These depths are then fit to a power function. During the continuing phase, the shape factor from Gilley's method is replaced by the shape factor from the previous time period and the process repeated until the beginning of recession. The infiltration function calculated during the last time period is then used as the infiltration function for the entire irrigation.

These methods make too many simplifying assumptions about the infiltration function, particularly if the infiltration over the entire irrigation is desired for both early periods during advance and for determining the final distribution. It would be advantageous to have a method that can reasonably describe the infiltration without necessarily resorting to a strict power function and be operable during the advance phase, the continuing phase (or simultaneous advance and recession) and the recession phase. The following method has many of these advantages and can be more readily used for comparisons with mathematical models of the irrigation process.

It is assumed that the advance between any two stations is linear, hence the name for this method, linear-station-advance. Then at any time t, the opportunity time distribution between stations is linear. Strelkoff (1977) developed an equation for the subsurface volume during linear advance (and thus linear opportunity time), namely

$$V_Z(t) = \frac{x \cdot Z(t)}{1 + a} \qquad [11]$$

Where $V_Z(t)$ is the subsurface volume at time t and x, Z(t) and a are as defined earlier. Equation [11] can be applied to each distance increment, with minor modifications. When advance reaches the first station, the subsurface volume can be found from $V_{Z_1}(t_1) = \Delta x_1\ Z(t_1)/(1 + a)$. The subsurface volume for the second distance increment, Δx_2, for advance to the second station, during the second time period, $(t_2 - t_1)$, is found from $V_{Z_2}(t_2) = \Delta x_2 \cdot Z(t_2 - t_1)/(1 + a)$. The subsurface volume for the first distance increment is no longer straight forward, since the total advance curve is no longer linear. We can find this volume by first assuming that advance continued at the same rate as in the first time period up to the end of the second time period. The advance distance would be $\Delta x_1 \cdot t_2/t_1$. Next, the volume not in Δx_1 can be calculated. The distance for this volume would be $(\Delta x_1 t_2/t_1) - \Delta x_1$ or $\Delta x_1\ [(t_2/t_1)-1]$. The resulting equation for the volume infiltrated in the first distance increment up to the end of the second time period is

$$V_{Z_1}(t_2) = \frac{t_2}{t_1} \cdot \frac{\Delta x_1 Z(t_2)}{1 + a} - \frac{t_2}{t_1} - 1 \cdot \frac{\Delta x_1 Z(t_2 - t_1)}{1 + a} \qquad [12]$$

The general equation for an entire border with N distance increments is found by summing the volumes over each increment and can be developed from equation [12], namely

$$V_Z(t_I) = \frac{1}{1 + a} \sum_{i=1}^{N} (x_i - x_{i-1}) \quad \frac{t_I - t_{i-1}}{t_i - t_{i-1}} \ Z(t_I - t_{i-1})$$

$$- \frac{t_I - t_{i-1}}{t_i - t_{i-1}} - 1 \quad Z(t_I - t_i) \qquad [13]$$

This equation is applicable during all phases of the irrigation, with the restrictions that $Z(t) = kt^a$ and that if the average recession time over a distance increment $t_R(\Delta x_i)$, is less than the time period under consideration, t_I, then t_R replaces t_I in equation [13]. With known values of $V_Z(t)$, $x(t)$ and t, equation [13] has two unknowns, k and a. A solution requires two equations representing two values of time, and can be found by trial and error. For an irrigation with M time periods, there are

$$\sum_{i=1}^{M} (i-1)$$

possible intake functions.

One way to determine a representative infiltration function would be to somehow average the k and a values for each time period (when used in combination with previous time periods) and then find an average over the entire irrigation. An alternative method is to determine the time necessary to infiltrate the average depth infiltrated up to a given time and average these values (again over combinations with previous time periods). This gives a time and depth point for each time value. These points can easily be fit with any infiltration function, thus this method is more versatile than previous methods.

It was noted during trial runs of this method, that the shape has very little effect on the values of average infiltration time, which was limited by the actual time value. It was then postulated that as a first trial, any value of a could be used. Then the above equation could be solved directly for k and the infiltration time for the average depth found. A best fit line through these points (with a = 0.5) was very close to that for the more complicated approach above. The slope of the new best fit line was then used and the process repeated. The k and a values for the second trial were identical to the more complicated method to 3 significant figures (as was the r^2 value). Thus the simpler, straightforward approach is now used, with considerable savings in computation time. (For roughness calculations a volume balance is used to find an adjusted k for each time period with the best-fit a.)

This method was used to estimate the infiltration function for run V-5 on the precision borders at the University of Arizona (Atchison, 1973). The results are shown in Fig. 3 along with results from Gilley's and Fangmeier's methods as given by Atchison, best fit power function, and a power function with a constant infiltration rate. There appears to be a discrepancy between the results of Atchison by Gilley's and Fangmeier's results and those presented here. They appear to differ by a constant, (i.e., different values of inflow rate or volume?). If the previous results were shifted upward, it appears as if both methods would reasonably describe the infiltration during the period over which they were calculated. The odd shape in the calculated values of infiltration are probably due to a number of factors including: inaccurate or erroneous data, spacial variations in infiltration or problems with the solution technique. The appearant increase in infiltration during recession is undoubtedly caused by the difficulty in determining recession even with water stage recorders.

APPLICATIONS TO SURFACE IRRIGATION

Example 1 - When accurate ring data can be obtained and reasonable estimates of the infiltration function determined, border irrigation models can be used to determine the best operating conditions for a particular field. This is not meant to imply that all conditions remain fixed, only that with knowledge of the range of conditions that occur, an operational policy can be developed which will give high efficiencies under all conditions.

Advance, recession and infiltration measurements were taken on the McDonnell-McElhaney farm on two separate days in 1977. During the first irrigation observed (5-26-77), the crop was starting to wilt, indicating water stress. This would probably represent the least soil moisture storage or the driest conditions for an irrigation. During the second irrigation observed (6-9-77), the soil moisture was at a high level with visible moisture at the surface, representing the wettest conditons. The infiltration functions for these two conditions represent the two extremes in infiltration and soil moisture. It was estimated that the soil profile could store less than 1 inch of available moisture per foot of soil . Thus, with a 5-6 ft rooting depth, water applications should be on the order of 3-4 inches. The other particulars for this field are: field length = 610 ft, field width = 170 ft., field slope = 0.00033 ft/ft, the crop is alfalfa with a suggested Manning roughness coefficient = 0.15, and power infiltration functions with constants = 2.9 and 2.2 in/hr^a and powers = 0.60 and 0.52 for the dry and wet conditions, respectfully. (The border was blocked to prevent runoff). The two infiltration functions along with the SCS intake family for that soil type are shown in Fig. 4. (The wet infiltration function used in this example and that given in Table 1 vary only slightly as shown in Fig. 4.)

The zero-inertia border-irrigation model was used to determine the maximum application efficiency and resulting uniformity for the two soil moisture conditions at 3 and 4 inches of net application and at 5 cfs intervals of flow rate. (Comparisons between field data and zero-inertia calculated advance and recession can be found in Clemmens, 1979). The results are presented in Tables 4 and 5. These efficiency values represent the maximum application efficiency (desired or net application/gross application) rounded to the nearest percent for whole minute application times with the criteria that no location receive less than 90% of the net application, and that 99% of the soil profile is filled based on the assumed net depth of application (99% storage efficiency). Note the high application efficiencies that are possible under the ranges of flow rate, net application and infiltration conditons. Also shown in Tables 4 and 5 (parentheses) are the efficiencies for these conditions if the borders had been level.

It could be argued that the higher application (4 inches) would be more practical on the dry soil, and the lesser application (3 inches) on the wet soil. Thus the farmer could achieve an efficiency of 90% at any flow rate from 15-20 cfs. Also notice that there is a trend in the optimum flow rate. For the wet conditon, applying more water changes the optimum from about 17 cfs to about 5 cfs. For the dry conditions, the change is smaller, from about 21-22 cfs to 18-19 cfs. Obiously, greater water applications require a lower flow rate to achieve the optimum efficiency for any soil moisture conditon.

Caution should be exercised in utilizing these types of results for the following reasons: The effects of surface roughness were not analyzed, variations in slope or roughness could cause changes in calculated versus actual advance and recession, definitive information on intake versus soil moisture or intake versus tillage practices were not evaluated, and the actual soil moisture deficit was not evaluated in detail. This example does point to the possible utilization of irrigation modeling.

Example 2 - Advance and recession were observed at the Wise farm on February 20, 1979, for a crop of winter wheat. Ring infiltration data was taken on basins 2 and 8. Accurate recession times were recorded on basin 7. The ring infiltration results are given in Table 1. The advance and recession data from basin 7 was used to find the adjusted infiltration constants. Infiltration data was taken for only about 3 hours and no final infiltration rate had been reached. The minimum recorded infiltration rate was about 0.28 in/hr. Equation [9] was used to determine estimates of the infiltration function for final infiltration rates of 0.3 and 0.2 in/hr with the value of a from the infiltration rate data. The calculations are summarized in Table 6.

These particular basins were of interest since the soil was a sandy loam, the slope was level and the runs were 960 ft. long. This represents somewhat of an extreme condition for level basins (long runs on a sandy soil). The basins were designed from the SCS Border Irrigation Handbook (USDA, 1974) based on an intake family of 1.0 in/hr. Three SCS intake family functions and the four adjusted ring data infiltration functions are plotted in Fig. 5. A reasonable soil moisture deficit for this soil (depending on crop and rooting depth) is 4 inches. Roughly 6 inches (5.88 Ac-in/Ac) were applied to basin 7 with a unit flow rate of 0.0784 cfs/ft. Advance was essentially completed at 154 minutes, although a few high spots along one side were not covered. When 5.4 inches were applied to basin 8 at 0.9955 cfs/ft, advance reached about only 800 ft. (Some water had reached the lower end by flowing down the borrow channel along the borderdike and covered the last 40 ft or so of the border.) Next 5.5 inches were applied to basin 2 at 0.1015 cfs/ft and the stream advanced to about 850 feet. According to the SCS design, the stream should have reached the end of the basin easily. The pertinent questions here are: What caused the advance to stop? If Infiltration was the cause, what was the infiltration function?

The zero-inertia border irrigation model was used to estimate maximum advance distances for these three basins with a Manning roughness value of 0.10 which is the value suggested by the SCS for wheat. The SCS 1.0 and 1.5 in/hr intake functions and the two adjusted functions in Table 6 were used. The results of these runs are presented in Table 7. Comparisons between calculated and computed advance distances indicated that the roughness value chosen was reasonable. Several things are appearant from these results. First, the shape of the infiltration function controlled the success of the irrigation. Next, the SCS infiltration families inadequately described the infiltration function for this field. Also, rules of thumb on the advance distance at cutoff are difficult to apply when infiltration functions vary so widely, particularly on level basins.

Example 3 - The best fit power infiltration function for the University of Arizona run V-5 given earlier and the Manning roughness coefficient determined from the same data were used as input to the zero-inertia border irrigation model. The roughness values calculated were similar to those found by Atchison (1973). The value used here, 0.087 $ft^{1/2}/sec$, was the average of the modes of the values calculated at each station, excluding the two end stations. The other particulars are given in Atchison (1973). Advance and recession curves are shown in Fig. 6 with the two sets of points being observed visually (+) and observed-computed with water stage recorders (X), the latter of which was used in the computations of infiltration and roughness. The differences between the observed-computed points and the zero-inertia solution stems from the difference between the calculated infiltration and the best-fit power function given in Fig. 3.

Water surface profiles (observed (+), and calculated) during advance, continuing phase, and recession are shown in Figs. 7-9. (Note that under the assumption of zero-inertia, the depth is zero at the downstream end of an open-ended border, Strelkoff, 1979). Figs. 10-12 give observed and calculated depth hydrographs at the upstream most and two intermediate stations. Some differences in recession times are attributable to the differences in infiltration. Considering the magnitude of the depth values (on the order of 1 inch) the correlations are excellent. Fig. 13 gives the observed (+) and zero inertia calculated runoff hydrographs. The total calculated runoff volume, 108.3 cubic feet, was less than half of one percent greater than that measured with a critical depth flume, 107.9 cubic feet. The goodness of fit for all these figures indicates that both the hydraulics of flow and the infiltration are both well predicted.

SUMMARY AND CONCLUSIONS:

Evaluating the infiltration of water into soils is the key to proper design and operation of border irrigation systems. A number of methods for evaluating infiltration were analyzed to determine their usefulness in relation to surface irrigation. From these results several other methods were developed to improve existing methods.

Ring infiltrometers have been used for many years. The results can be useful provided that the ring is properly installed and operated, the measurements are made during an irrigation, and a volume balance is maintained in the border. Existing methods for estimating infiltration from rings used the infiltrated volume versus time as a power function to adjust the ring data to achieve a volume balance. In many cases, infiltration does not follow a power function through the entire irrigation since many soils appear to reach a constant infiltration rate during the irrigation. Two methods were developed to adjust the ring data to achieve a volume balance for soils which reach a constant (final) infiltration rate.

Bouwer's method for estimating infiltration in irrigation borders was used on 12 borders on the University of Arizona Cotton Research Center. We found that for a large number of borders or borders with very uniform infiltration that the method worked reasonably well. However, for fields with considerable spatial variability in infiltration, the method was not reliable. Difficulty in estimating recession times also decreased the usability of the method. The zero-inertia model was used to obtain precise advance and recession for a known infiltration function. Bouwer's method was then evaluated for a variety of time increment combinations. The time increments chosen had a significant effect on the results.

A new method was developed for estimating infiltration when (surface) water depth profiles at different time intervals are known. The method is an improvement on Fangmeier's method which assumes a power infiltration function. The new method, linear station advance, gives a series of discrete points which can be fit with any appropriate function. This method was used on data obtained on the precision border at the University of Arizona. The results showed that infiltration did not closely follow a power function. The results of this method were used as input to the zero-inertia model, and the actual and predicted surface water profiles, depth hydrographs, and runoff hydrographs were compared. Agreement was good in all cases.

The zero-inertia model was also used to determine the effects of infiltration on surface irrigation efficiencies. The model was used to determine potential efficiencies on a particular field near Wellton, AZ, where previous studies had determined a range in infiltration for extreme conditions. The results could be used to develop an optimal water management policy. Field tests on another field (level basin) in the Wellton-Mohawk Valley resulted in the irrigation stream not reaching the end of the field. Both the Soil Conservation Service (SCS) design criteria and the zero-inertia model indicated that it should have reached the end of the field, provided the SCS intake family used for the infiltration function was correct. Analysis showed that the shape of the actual infiltration function was radically different from the SCS families. The zero-inertia model verified that indeed the stream would not reach the end of the field when the actual infiltration function was used.

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Table 1: Ring Data Results - Power Functions

	Source/Location	Date	Cumulative Infiltration a	Cumulative Infiltration $K(in/hr^a)$ best fit	Cumulative Infiltration $K(in/hr^a)$ adjusted	Infiltration Rate a	Infiltration Rate $K(in/hr^a)$ best fit	Infiltration Rate $K(in/hr^a)$ adjusted
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1.	Criddle	1956	.570	5.09		.505	5.93	
2.	Burns (Dedrick)	Jun 16, 1976	.408	0.608		.378	0.732	
3.	Klingenberg (Holeman)	May 9, 1977	.510	1.06		.442	1.22	
4.	McDonnell #6	May 26, 1977	.606	2.55	2.86	.595	2.90	2.90
5.	McDonnell #6	Jun 9, 1977	.556	2.15	2.10	.562	2.01	2.07
6.	Naquin (Dedrick)	Aug 10, 1976	.375	1.10		.303	1.40	
7.	Naquin (Dedrick)	Sep 1, 1976	.397	0.553		.299	0.733	
8.	CRC-F3	Sep 19, 1977	.642	1.97	3.90	.612	2.00	4.03
9.	CRC-A3	Sep 20, 1977	.792	2.33	3.50	.811	2.51	3.47
10.	CRC-E3-6	Oct 12, 1977	.592	1.16	2.76	.603	1.17	2.70
11.	CRC-C3-1	Sep 21, 1978	.407	1.48	2.30	.292	1.89	2.64
12.	CRC-C3-3	Sep 21, 1978	.428	1.17	2.06	.385	1.30	2.15
13.	CRC-C3-1	Oct 11, 1978	.475	0.937	1.69	.463	1.017	1.73
14.	CRC-C3-3	Oct 11, 1978	.469	0.747	1.72	.414	0.806	1.88
15.	WISE - 2	Feb 20, 1979	.348	3.01	2.77	.089	7.13	4.84
16.	CRC-C3-1	Apr 2, 1979	.486	0.542	1.24	.517	0.507	1.14

Table 2. Ring Data Results - Power functions with final intake

	Border 1 Cumulative	Border 1 Rate	Border 3 Cumulative	Border 3 Rate
best fit a	0.407	0.292	0.428	0.385
best fit k	1.48	1.89	1.17	1.30
adjusted k	2.30	2.64	2.06	2.15
estimated i_f	0.471	0.471	0.447	0.447
best fit k	1.53	1.98	1.17	1.30
best fit a	0.421	0.242	0.429	0.325
adjusted i_f	0.664	0.578	0.723	0.679
adjusted k	2.17	2.43	1.89	1.97

Table 3. Solution from Bouwer's Method

	Bouwer's		Actual	
time (min) (1)	$\bar{i}$ (in/hr) (2)	Z in (3)	$\bar{i}$ (in/hr) (4)	Z in (5)
90	1.72	2.58	1.60	2.40
210	0.164	2.91	0.230	2.86
450	0.166	3.57	0.125	3.36
60	2.54	2.54	2.20	2.20
180	0.132	2.80	0.285	2.77
420	0.174	3.50	0.135	3.31
120	1.40	2.80	1.27	2.54
180	0.0	2.80	0.230	2.77
300	0.174	3.15	0.155	3.08

Table 4. Maximum Application Efficiencies for Dry Conditions

Maximum Efficiency (%)

Net Application	Flow Rate (CFS)			
	10	15	20	25
3"	70	74	77(66)	76(67)
4"	87	92	96(83)	90(86)

Uniformity

Net Application	Flow Rate (CFS)			
	10	15	20	25
3"	.90	.93	.93(.91)	.97(.91)
4"	.94	.98	.98(.93)	.96(.93)

Application Time (Min)

Net Application	Flow Rate (CFS)			
	10	15	20	25
3"	62	39	28(33)	23(26)
4"	66	42	30(35)	26(27)

Table 5. Maximum Application Efficiencies for Wet Conditions.

Maximum Efficiency (%)

Net Application	Flow Rate (CFS)			
	5	10	15	20
3"	79	87	90(76)	90(77)
4"	94	85	80(88)	80(91)

Uniformity

Net Application	Flow Rate (CFS)			
	5	10	15	20
3"	.90	.97	.97(.93)	.99(.94)
4"	.98	.93	.92(.96)	.91(.97)

Application Time (Min)

Net Application	Flow Rate (CFS)			
	5	10	15	20
3"	111	50	32(38)	24(28)
4"	122	68	48(44)	36(32)

Table 6. Summary of Infiltration Calculations for Example 2 - Wise Farm, Basin 7.

Average opportunity time = 8.63 hours
Average depth applied = 5.88 inches
a = 0.09

	Final Intake Rate	
	0.2 in/hr	0.3 in/hr
ϕ	4.15 in	3.29 in
C	2.22 in/hr	3.33 in/hr
k	4.27 in/hr[a]	3.59 in/hr[a]
t_f	2.05 hrs	1.08 hrs
t_f	4.56 in	3.62 in
Z(8.63)	5.88 in	5.88 in

Table 7. Results of Advance on Zero-Inertia Model

	Basin 7	Basin 8	Basin 9
Observed	finished	to 780-800 ft	to 850-900 ft
i_f = 0.2 in/hr	finished	to 900 ft	to 912 ft
i_f = 0.3 in/hr	finished	finished	finished
SCS 1 in/hr	finished	finished	finished
SCS 1.5 in/hr	finished	finished	finished

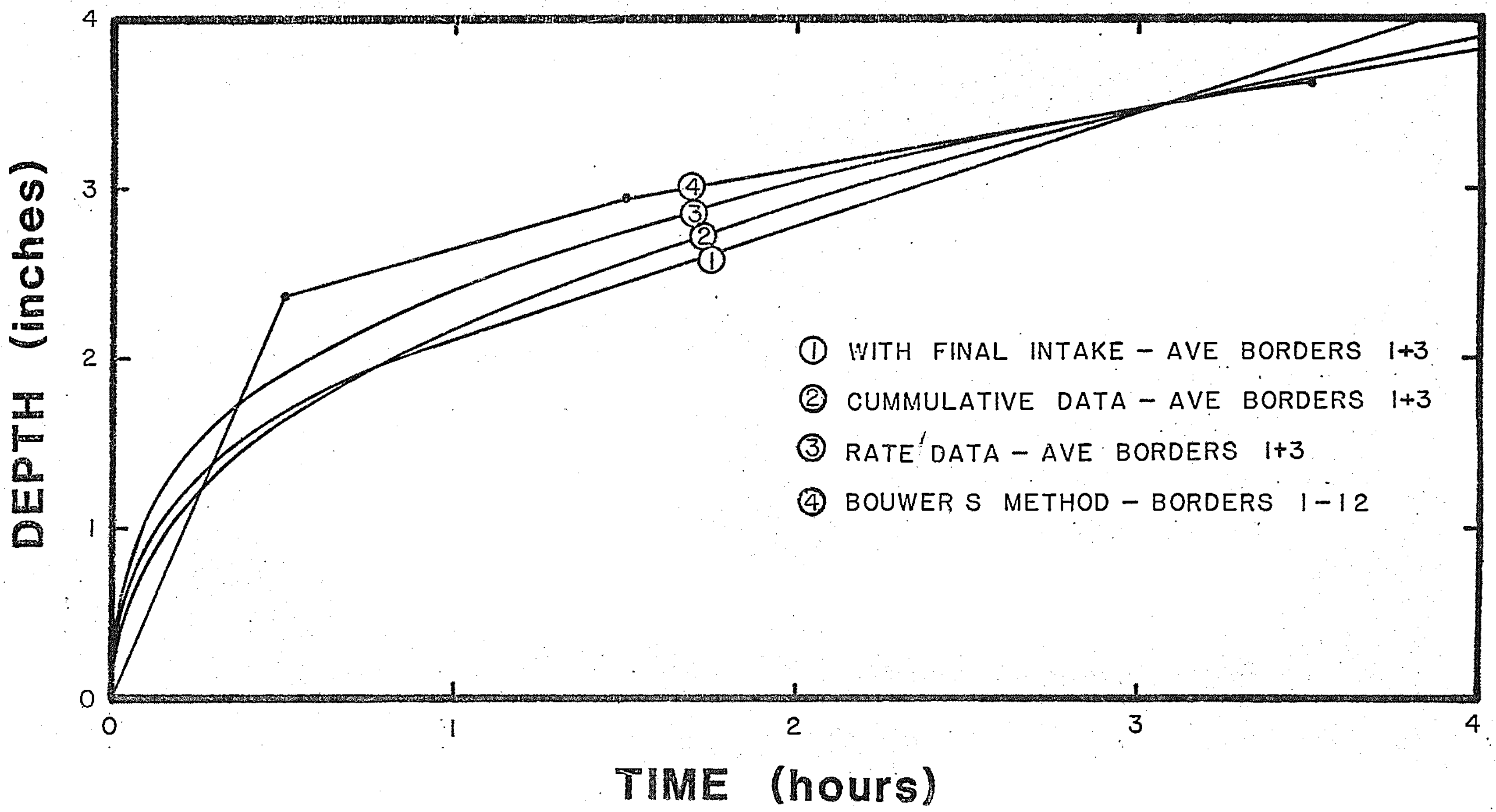

Fig. 1. Cumulative infiltration curves from irrigation at the Cotton Research Center. September 21, 1978.

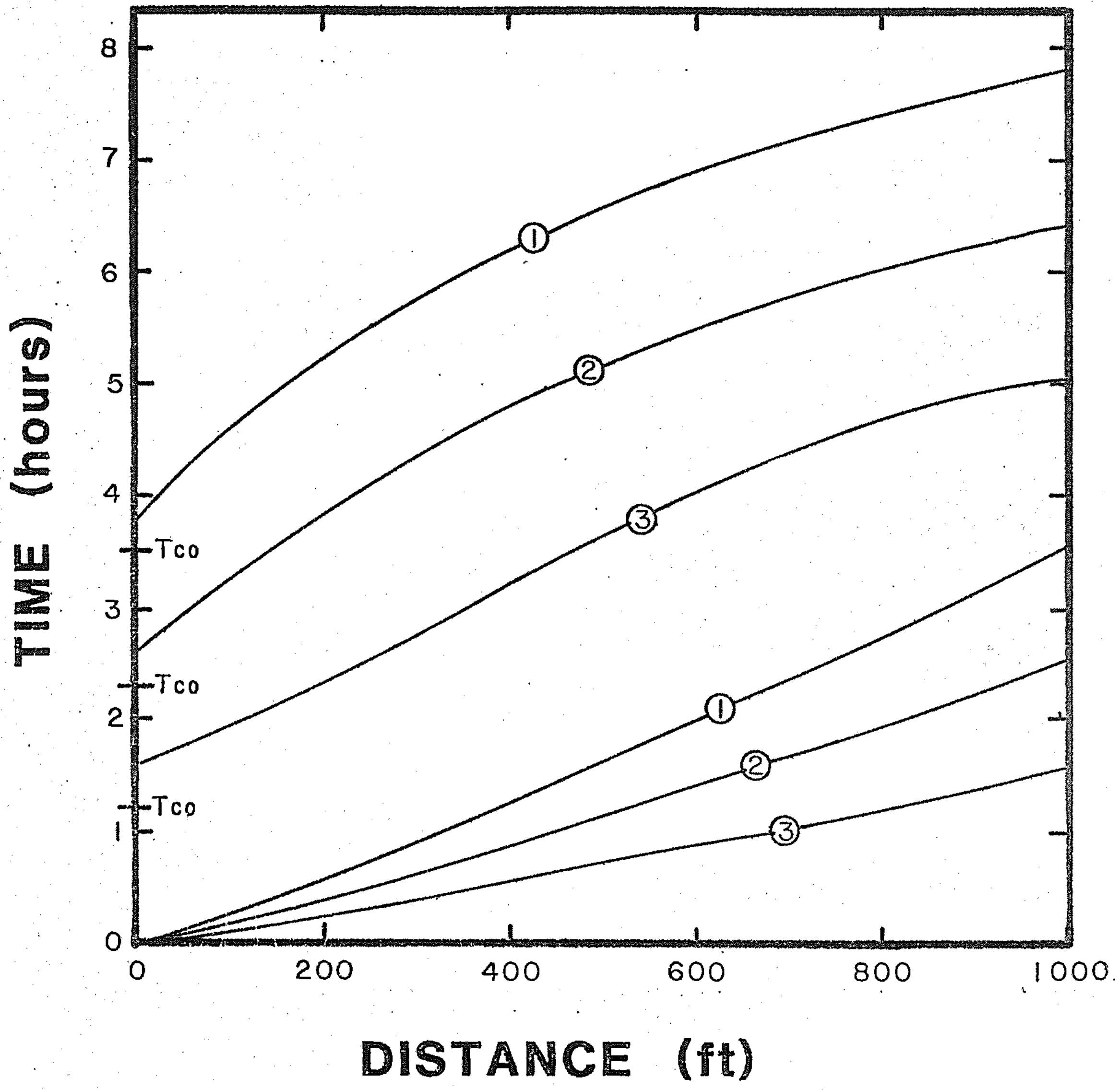

Fig. 2: Advance and recession curves used to find solutions by Bouwer's method.

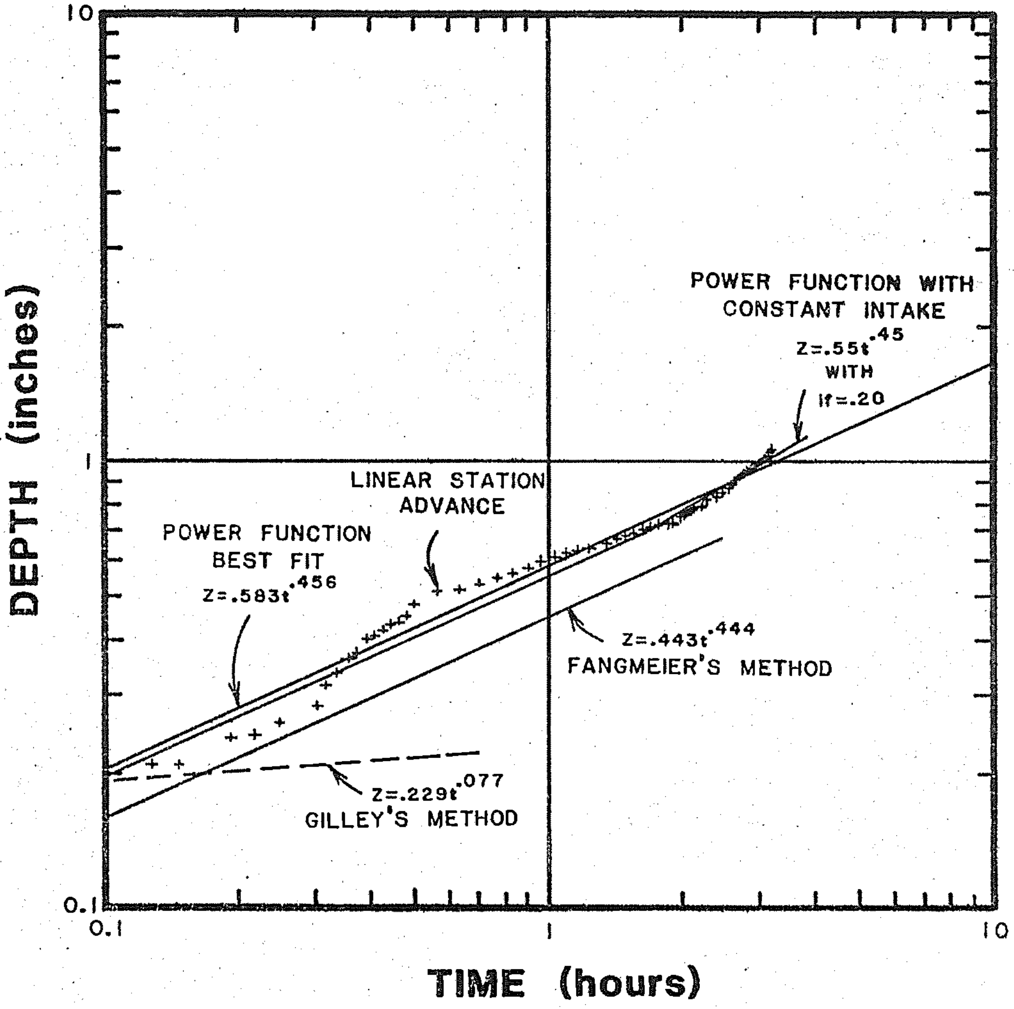

Fig. 3. Cumulative infiltration for U of A run V-5.

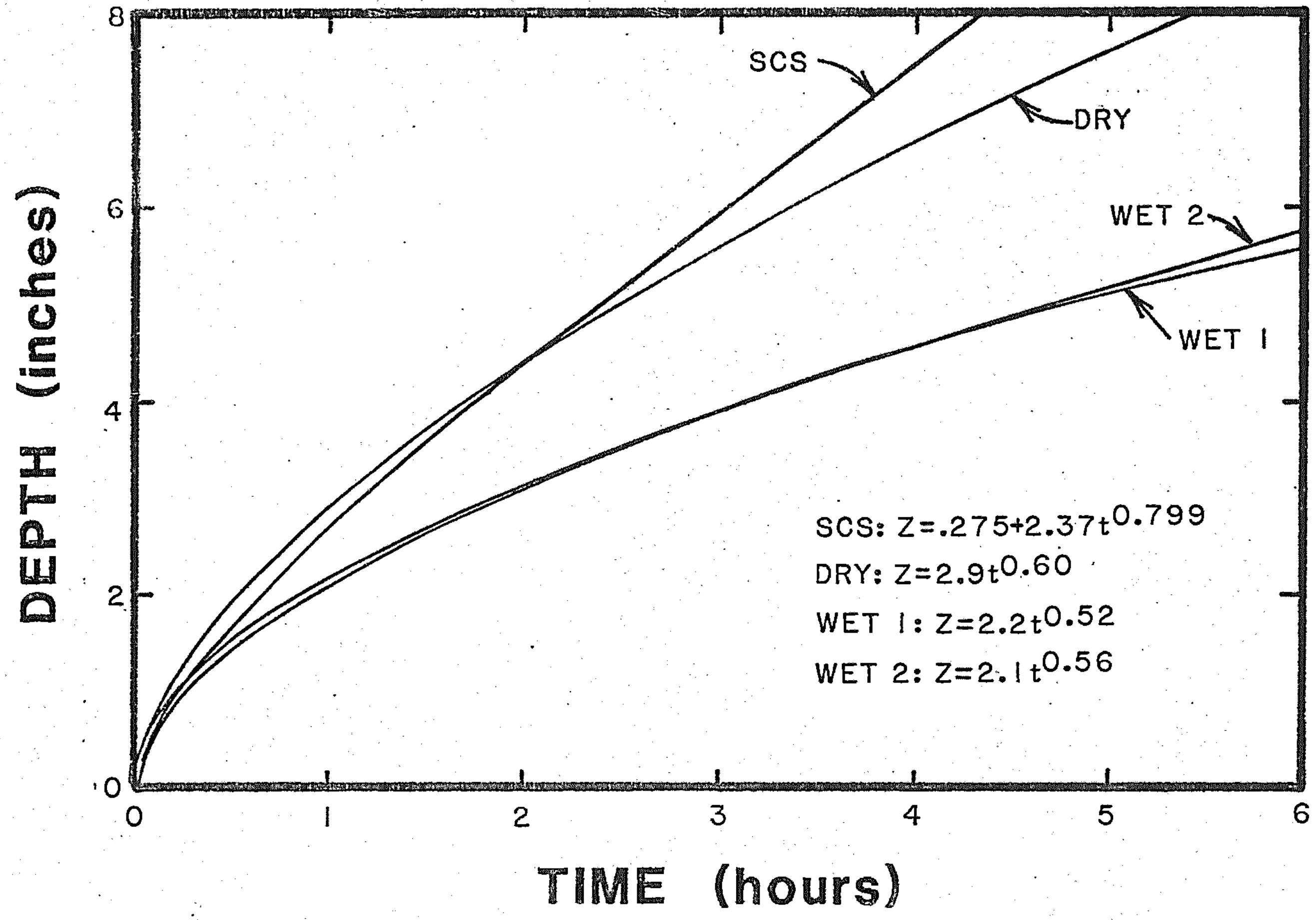

Fig. 4. Cumulative infiltration for a field on the McDonnel-McElhaney farm (1977).

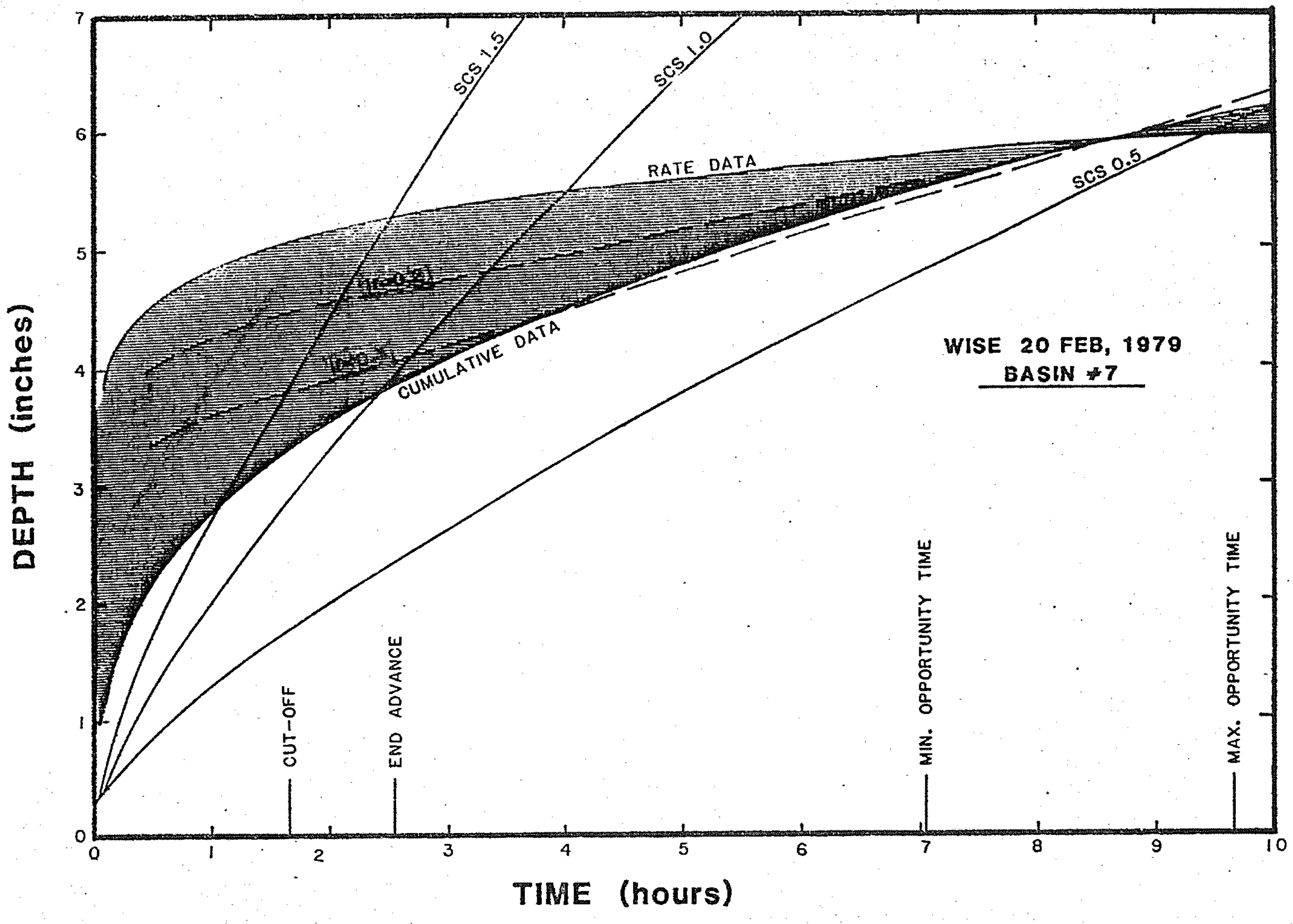

Fig. 5. Cumulative infiltration for a field on the Wise farm. February 20, 1979.

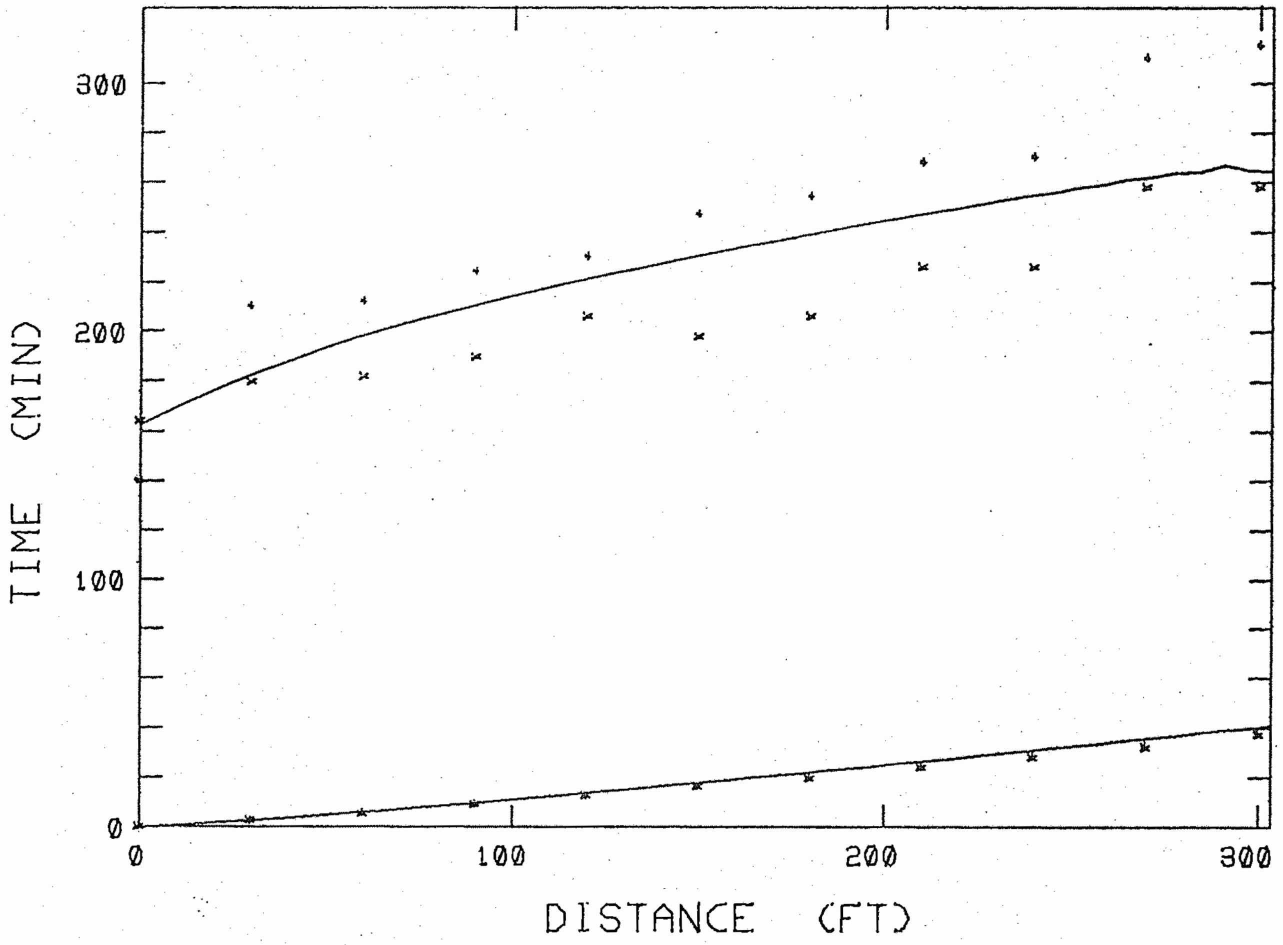

Fig. 6. Advance and recession for U of A run V-5.

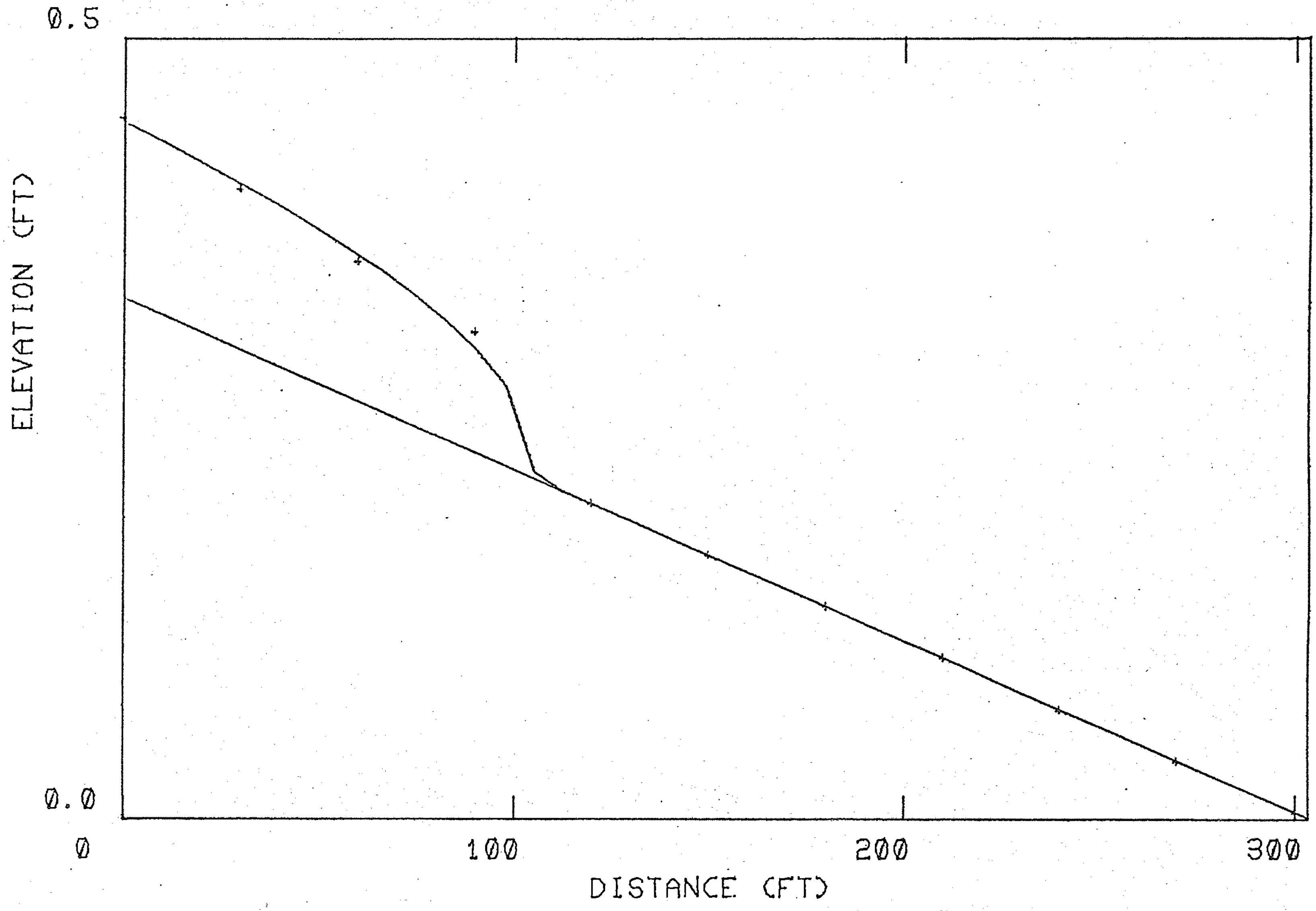

Fig. 7. Water surface profile at t = 12.9 min. for U of A run V-5.

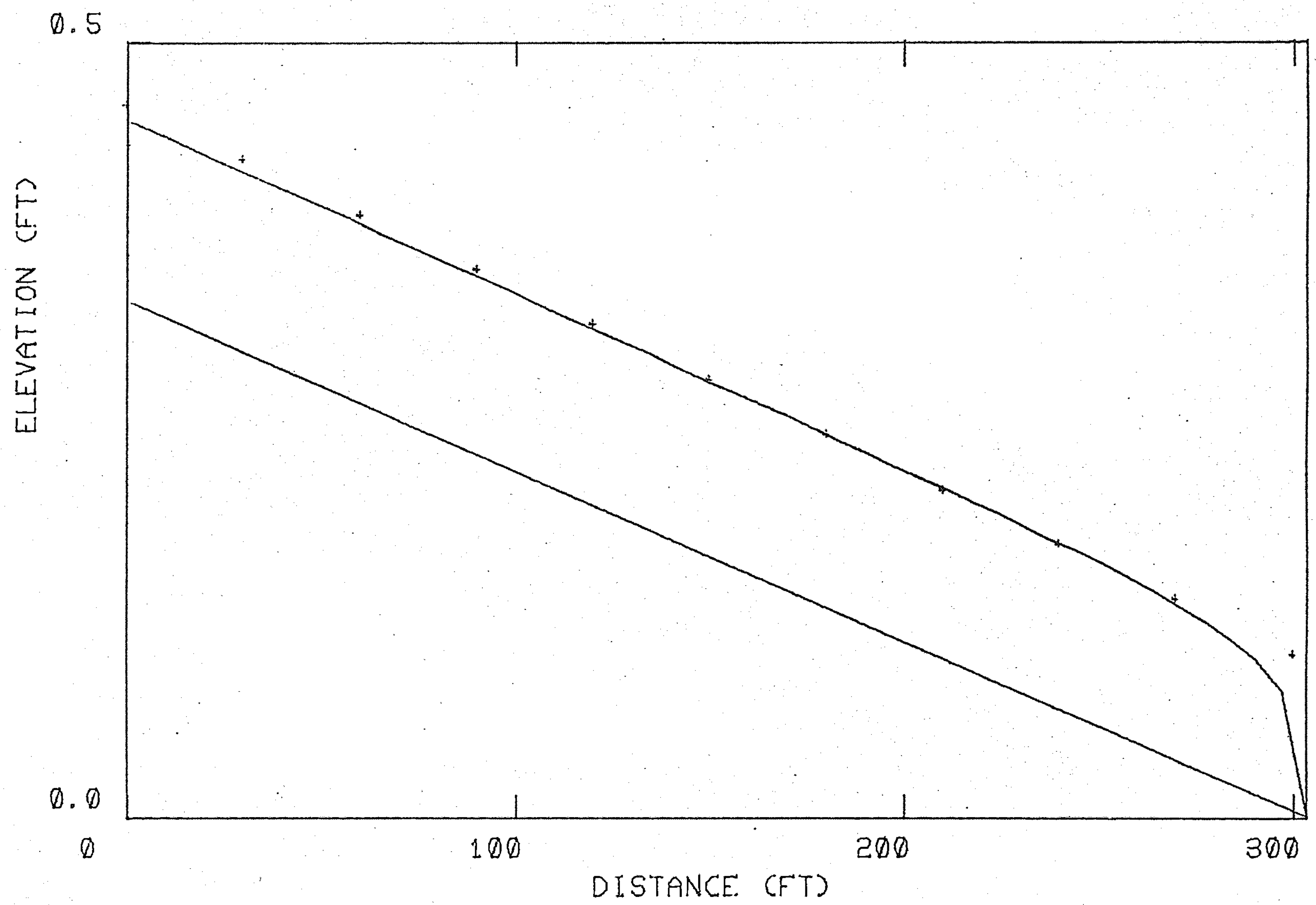

Fig. 8. Water surface profile at t = 100 min. for U of A run V-5.

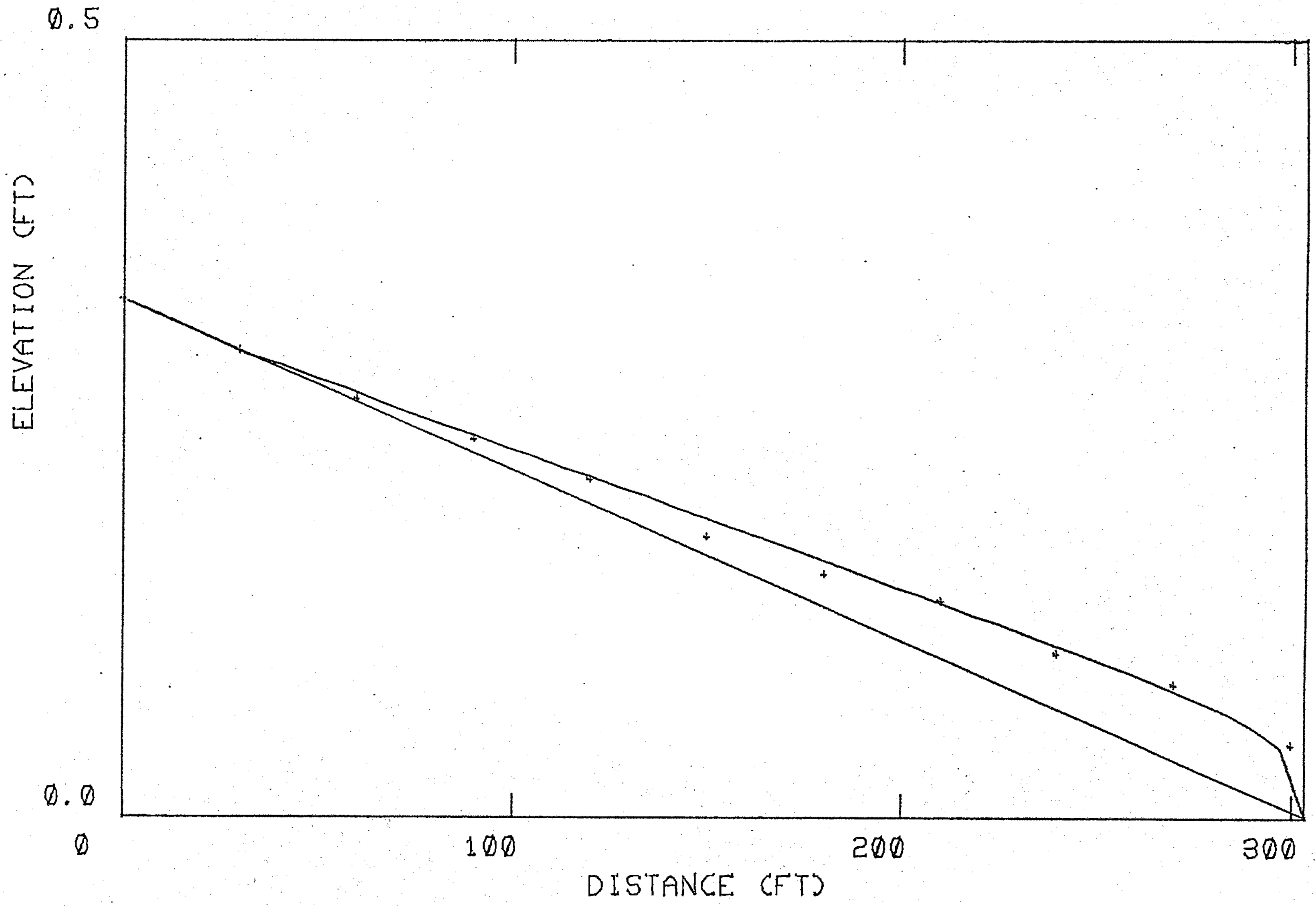

Fig. 9. Water surface profile at t = 180 min. for U of A run V-5.

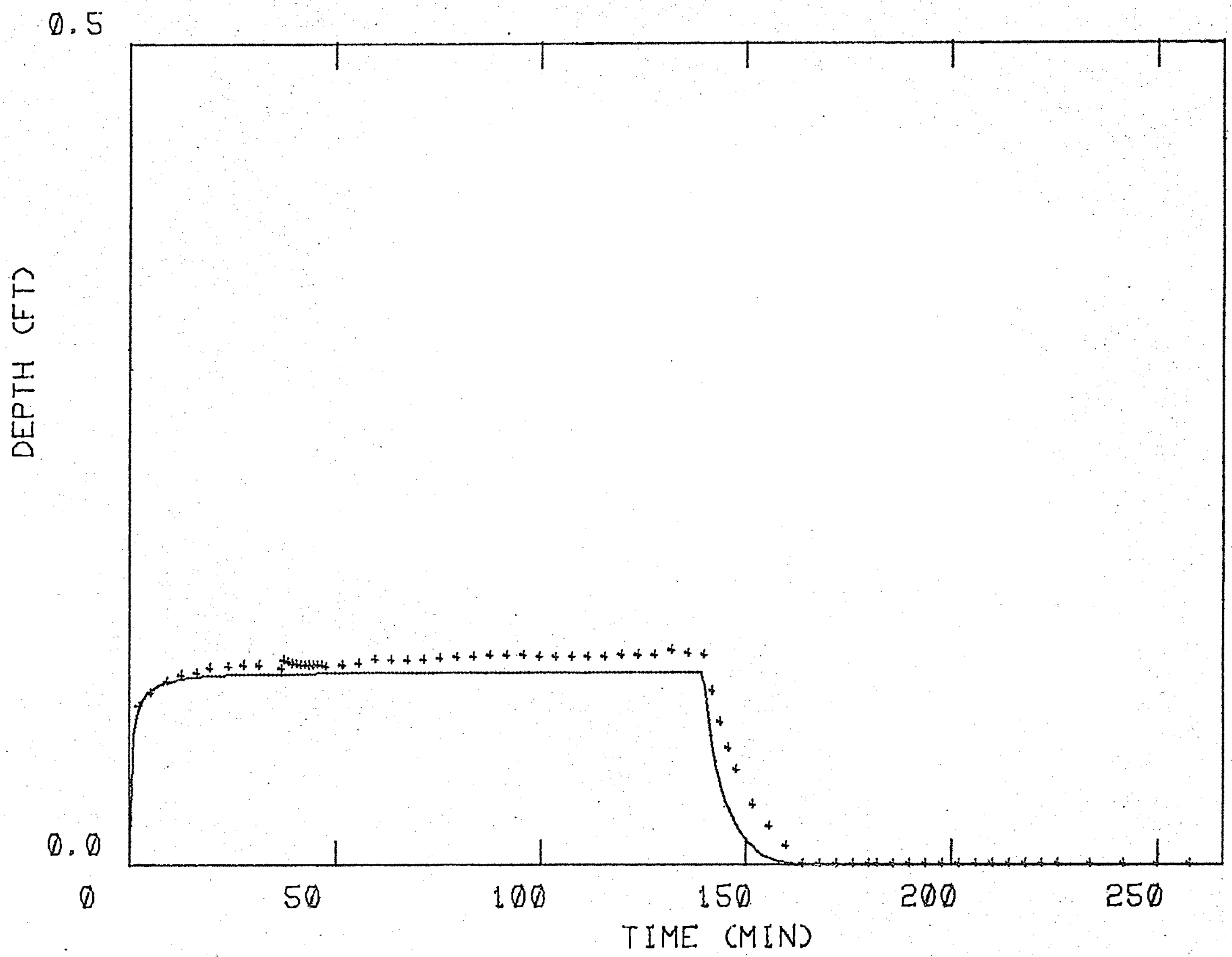

Fig. 10. Water depth hydrograph at X = 0 ft. for U of A run V-5.

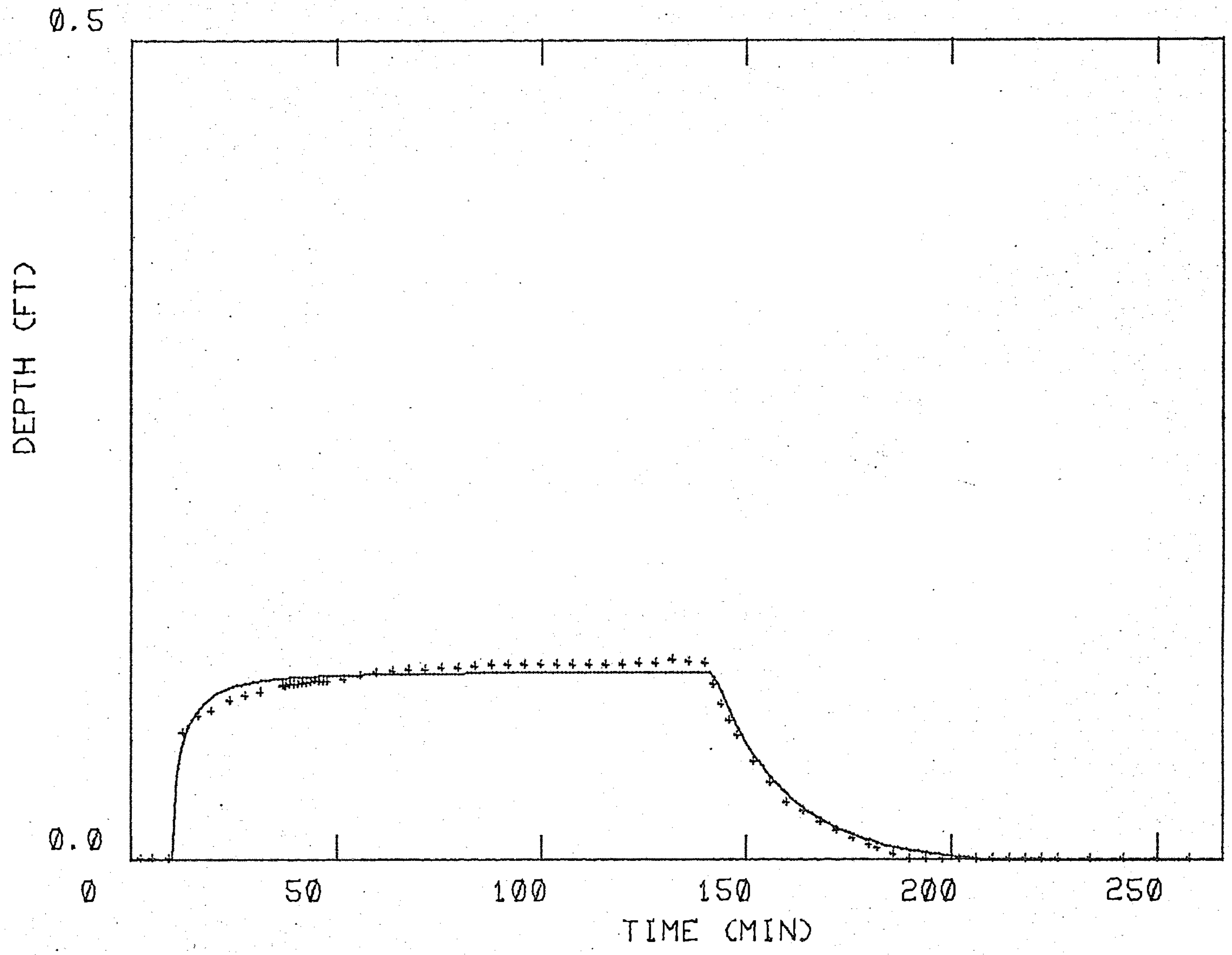

Fig. 11. Water depth hydrograph at X = 90 ft. for U of A run V-5.

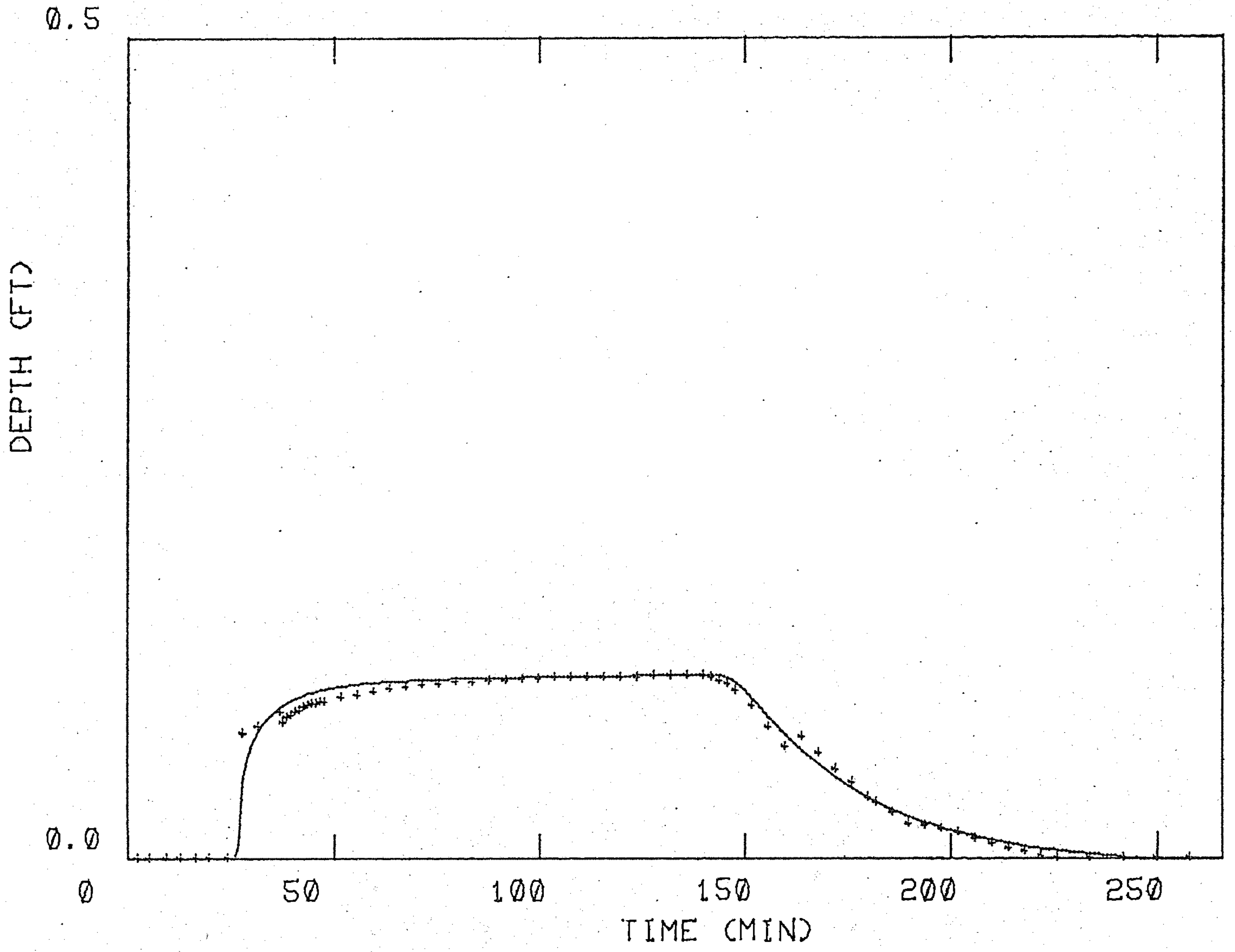

Fig. 12. Water depth hydrogrpaph at X = 210 ft. for U of A run V-5.

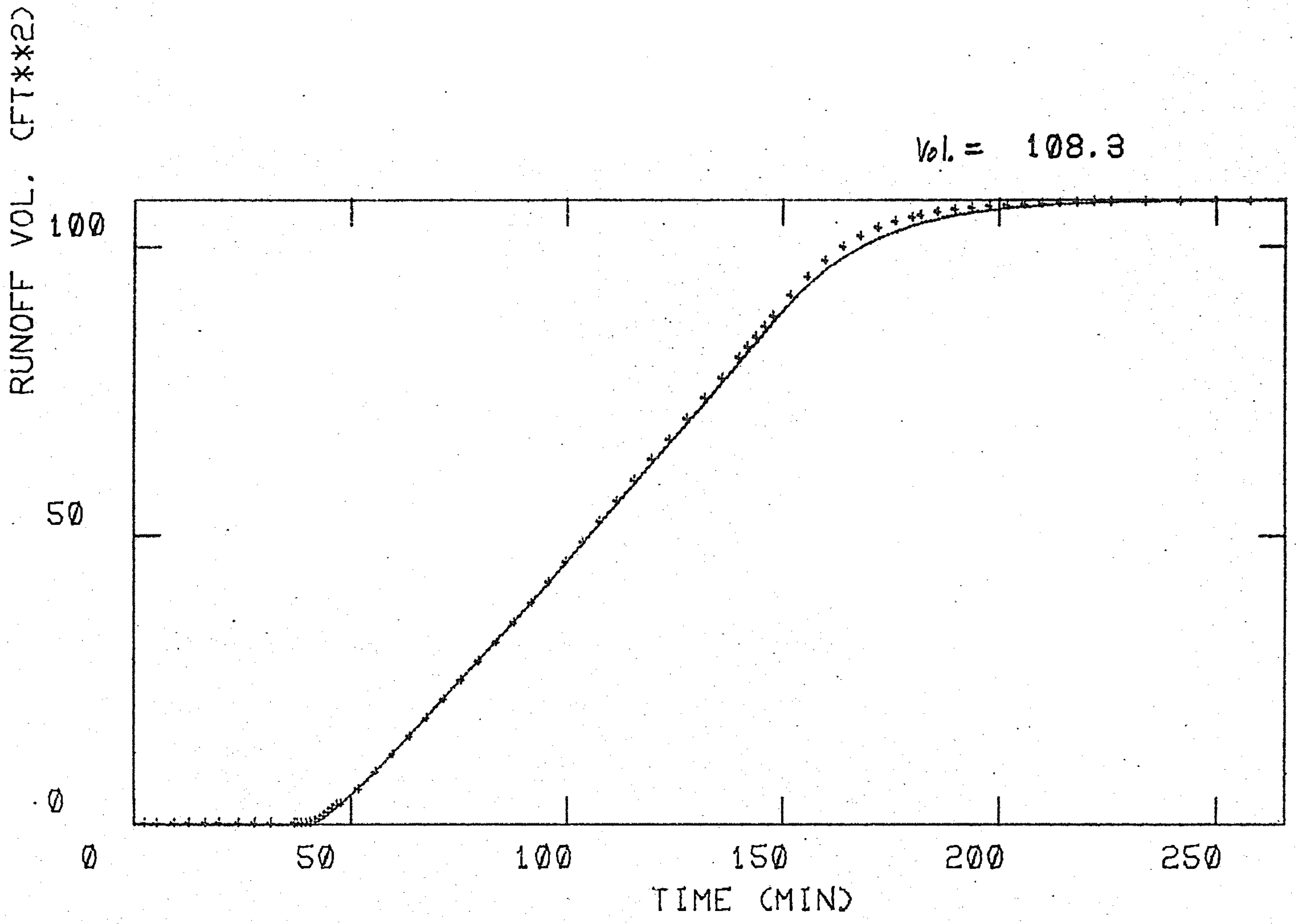

Fig. 13. Runoff volume curve for U of A run V-5.

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

NRP: 20760 CRIS WORK UNIT: 5510-20760-001

INTRODUCTION:

Research conducted under the project outline this year resulted in the publication of two papers on the subject of evaporation, the preparation of three papers on the complexities of obtaining plant canopy temperatures by means of infrared thermometry, the preparation of four papers on the utility of the stress-degree-day technique for employing remotely sensed canopy temperatures to schedule irrigations and predict crop yields, and the preparation of three papers on the theory and use of spectral reflectances to evaluate standing crop conditions. A paper on the potential of crop flourescence intensity to convey information on water stress severity was also prepared in cooperation with scientists from the USGS and EPA. A major field experiment on the use of the stress-degree-day concept for scheduling irrigations on wheat was completed, and a preliminary analysis of the data was initiated. NASA cooperators were involved with some of the remote canopy temperature assessment work; while scientists from the University of California at Davis helped in some of the stress-degree-day experiments.

Part A: Evaporation

1. Idso, S. B., Reginato, R. J., and Jackson, R. D. Calculation of evaporation during the three stages of soil drying. Water Resources Res. 15:487-488. 1979.

A single equation was developed to calculate daily evaporation rates during all three stages of soil drying. The only required input data are daily incoming and reflected solar radiation and maximum and minimum air and soil surface temperatures. Experiments demonstrating the validity of the equation were conducted on an Avondale loam soil at Phoenix, Arizona, under a wide range of climatic conditions. It was shown that the effects of many important meteorological parameters are automatically accounted for by the direct measurement of the soil surface temperature.

2. Idso, S. B. Discussion "Evapotranspiration from water hyacinth (Eichhornia crassipes (Mart.) Solms) in Texas reservoirs," by A. R. Benton, Jr., W. P. James, and J. W. Rouse, Jr. Water Resources Bull. 15:1466-1467. 1979.

For the past 30 years, a serious error has been propagated in the scientific literature relative to the amount of excess evaporation that is induced by water hyacinth infestation of reservoirs. Such infestation has often been assumed to increase evaporation 3-fold over that for an open water surface, while in reality it probably decreases it. A review of past experimental work pertinent to this topic is presented. Since millions of dollars are spent annually to control this aquatic weed, it is important that its true effect on evaporative water loss be properly understood, so that it is not removed for the wrong reason and evaporative water loss be enhanced rather than retarded.

Part B: Measurement Complexities

3. Millard, J. P., Reginato, R. J., Goettelman, R. C., Idso, S. B., Jackson, R. D., and LeRoy, M. J. Experimental relations between airborne and ground measured wheat canopy temperatures. Photogrametric Engineering and Remote Sensing, in press.

An intensive 23-day airborne and ground measurement program was conducted at Phoenix, Arizona, in 1977 to compare airborne acquired wheat canopy temperatures with simultaneous ground measurements. For canopies that covered at least 85 percent of the soil surface, airborne measurements differed from ground measurements of plant temperature by less than 2°C, which was considered adequate for implementation of a water management program based on the stress-degree-day concept.

4. Kimes, D. S., Idso, S. B., Pinter, P. J., Jr., Jackson, R. D., and Reginato, R. J. Complexities of nadir-looking radiometric temperature measurements of plant canopies. Appl. Opt., submitted.

This paper demonstrates the relationship between the mean temperature of a field, as sensed by an infrared thermometer looking directly downward, and the different temperatures of the component plant and soil layers that make up the composite signal.

Effective radiant temperatures (ERT's) of five wheat canopies in different stages of development were measured during morning and noon periods. The observed variability in nadir sensor response was quantitatively described as a function of canopy structure and the vertical temperature profile of canopy components. In many cases, the nadir sensor ERT was a poor measure of vegetation temperature, due to effects of soil emissions. Strong vertical temperature profiles of vegetation components were also observed. The theory and measurements presented document that remote measurements of vegetation canopy temperatures cannot be made indiscriminately over large spatial regions without consideration of the underlying physical principles.

5. Kimes, D. S., Idso, S. B., Pinter, P. J., Jr., Reginato, R. J., and Jackson, R. D. View angle effects in the radiometric measurement of plant canopy temperatures. Remote Sens. of Environ., submitted.

This paper demonstrates the great variation in crop temperature that results from viewing a crop canopy from a variety of different angles from the zenith, thus pointing out the importance of determining the optimum view angle needed to obtain a true crop canopy temperature.

The thermal infrared sensor response from a wheat canopy was shown to be extremely non-Lambertian, due to spatial variations in energy flow processes, with the effective radiant temperature of the sensor varying as much as 13°C with changing view angle. This variation of sensor response was accurately quantified (rms of deviations between theoretical and measured responses reduced to 1.1°C) as a function of vegetation canopy geometry, vertical temperature distribution of canopy components, and sensor view angle. The results have important implications for optimizing sensor view angles for remote sensing missions.

Part C: Stress-Degree-Day Concept Progress

6. Idso, S. B., Reginato, R. J., Hatfield, J. L., Walker, G. K., Jackson, R. D., and Pinter, P. J., Jr. A generalization of the stress-degree-day concept of yield prediction to accommodate a diversity of crops. Agric. Meteorol., in press.

Crop yield prediction is an activity of great importance in all parts of the world, and the use of remote sensing techniques to improve its accuracy and timeliness is a research goal of high priority to most of the earth's industrialized nations. In this paper we pool a great diversity of data we have obtained to develop a single predictive expression for crop yield, based primarily on measurements of crop canopy temperature. This one relationship has been found to be applicable to sorghum, soybeans, red kidney beans, alfalfa, barley, and two varieties of wheat, some of which crops were grown in three different locations and in three different years, with a variety of planting dates, seeding rates, and irrigation practices. Some speculation on reasons for the existance of such a general relationship are presented, along with suggestions for possible future refinements.

7. Idso, S. B., Reginato, R. J., Pinter, P. J., Jr., and Jackson, R. D. A technique for evaluating canopy diffusion resistances and evaporation via infrared thermometry. J. Appl. Meteorol., submitted.

Results of several experiments relating surface-air temperature differentials ($T_S - T_A$) of open water, bare soil, and crop canopies to air vapor pressure deficit ($e_A^* - e_A$) and net radiant heat load (R_N) are presented. It is shown that for open water and potentially evaporating bare soil, there is no unique relationship of the form $T_S - T_A = a + b\ (e_A^* - e_A)$ that is independent of R_N. For plant canopies, however, such a relationship does exist; and it appears to be the definitive criterion for the existence of a potential evaporation state. Consequently, it is shown that for a plant canopy satisfying this condition, the product of stomatal diffusion resistence (r_s) and

R_N is a constant, enabling one to specify r_s from measurements of only R_N, once a and b are determined. Furthermore, it is possible to derive an equation for potential evaporation from plant canopies of the form $E = K R_N (e_s* - e_A)$, where e_s* is the saturated vapor pressure at the mean radiant temperature of the canopy and K is a "crop coefficient," dependent only on certain physical constants and the values of a and b.

8. Idso, S. B., Pinter, P. J., Jr., Reginato, R. J., and Jackson, R. D. The stress-degree-day technique as an "early warning" indicator of impending water stress in wheat. Irrigation Sci., submitted.

Experiments on several differently irrigated plots of wheat at Phoenix, Arizona, have indicated that yield reductions due to water stresses will not occur as long as no more than 65 percent of the available water in the crop's root zone is extracted. They also demonstrate that a new form of the stress-degree-day concept that requires knowledge of only crop canopy and air dry- and wet-bulb temperature can readily detect soil water content changes throughout the entire range of soil water availability from 0 to 100 percent. Consequently, this approach to irrigation scheduling can give more than sufficient advance warning of the need to irrigate wheat on a specific day.

Part D: Spectral Reflectance Progress

9. Jackson, R. D., Reginato, R. J., Pinter, P. J., Jr., and Idso, S.B. Plant canopy information extraction from composite scene reflectance of row crops. Applied Optics:18, 3775-3782. 1979.

Many agricultural crops are planted in rows. Thus, for much of the growing season, a remote sensor will "see" both soils and plants within each resolution element. The relative amounts of soils and plants, the degree of shading, and the row orientation with respect to the sun all affect the data obtained with a remote sensor. As an aid in the interpretation of remotely sensed data from row crops with incomplete canopies, a model was developed that allowed the calculation of the fractions of sunlit soil, shaded soil, sunlit vegetation, and shaded vegetation for each resolution element in a scan of a remote sensor for a given set of conditions (plant cover, plant height/width ratio, row spacing, row orientation, time of day, day of year, latitude, and size of resolution element). Using measured representative reflectances of the four surfaces, composite reflectances were calculated as a function of view angle. Also, representative temperatures for each surface were used to simulate composite temperatures viewed by an infrared scanner. With composite reflectances and temperatures known as a function of view angle, ways were explored to extract plant cover and plant temperature data from the composite data.

10. Jackson, R. D., Pinter, P. J., Jr., Idso, S. B., and Reginato, R. J. Wheat spectral reflectance: Interactions between crop configuration, sun elevation, and azimuth angle. Applied Optics, 18, 3730-3732. 1979.

Use of satellite data for agricultural applications such as estimation of green biomass and as input into yield models requires repetitive imagery over the same location. Although Landsat passes over a particular U. S. Location at about the same time of day (once every 18 days), the sun angle at that time of day changes dramatically with season and affects the reflectance of light from the earth's surface. In addition to solar elevation, crop configuration (row direction, row spacing, plant height, etc.) causes the sun's azimuth angle to affect spectral reflectance, an aspect heretofore not examined. We conducted an experiment in which wheat was planted in three plots: one was very dense with no row structure; two were in rows spaced about 0.3 meter apart, with rows running north-south in one and east-west in the other. Reflectance measurements were made about every 1/2 hour throughout one day when the plants were about 0.35 m tall and all at the same growth stage. We found that crop configuration is a major determinant of spectral reflectance, probably sufficient to obscure varietal differences, and should be accounted for in the interpretation of multidate imagery.

11. Jackson, R. D., Pinter, P. J., Jr., Reginato, R. J., and Idso, S. B. Shadows as a factor in diurnal spectral reflectance variations of a wheat crop. (Submitted to Remote Sensing of Environment.)

Experimental data and theoretical calculations showed that spectral reflectances and two vegetation indices calculated from reflectances of row-planted crops varied up to one-half the total possible range of values during the course of a day. This variability was due to changing shade conditions which markedly alter the reflectance properties of a composite soil and plant scene. Soil between north-south rows will be shaded in the morning and afternoon, while east-west rows have less shade at mid-morning and mid-afternoon than at solar noon. The degree of shading depends upon the height of the plants and the row spacing. The variation in reflectance must be accounted for when using ground, truck, or aircraft-based remote sensors to gather support data for satellites that pass over at a fixed time of day.

12. Pinter, P. J., Jr., Jackson, R. D., Idso, S. B., and Reginato, R. J. Multidate spectral reflectances as predictors of yield in water stressed small grains. (Submitted to International Journal of Remote Sensing.)

Spectral reflectances of small grains at Phoenix, Arizona, were measured during two growing seasons using a hand-held radiometer, the Exotech Model 100A, that had a spectral bandpass configuration similar to scanning radiometers aboard Landsat 2 and 3. During the period of grain filling, yields of two wheat and one barley varieties were well correlated with the integrated daily values of a modified vegetation index derived from reflectances in MSS Bands 5 and 7 (0.6 to 0.7 and 0.8 to 1.1 μm, respectively). The derived model accounted for 88% of the variability in yields from 103 to 656 g/m^2 which were due to differential experimental soil moisture conditions (20- to 70-cm applied water).

13. McFarlane, J. C., Watson, R. D., Theisen, A. F., Jackson, R. D., Ehrler, W. L., Pinter, P. J., Jr., Idso, S. B., and Reginato, R. J. Plant stress detection by remote measurement of flourescense. (To be submitted to Applied Optics.)

Fraunhofer lines are extremely narrow regions of the electromagnetic spectrum in which little or no solar radiation reaches the earth. Interaction of solar radiation with certain substances such as chlorophyll in plants cause them to emit radiation in these narrow regions, a process called fluorescence. The degree of fluorescence attributable to chlorophyll is related to the photosynthetic rate and hence, water stress. A device called a Fraunhofer Line Discriminator, built by the U. S. Geological Survey, has been successfully used to identify ore deposits, contamination of water systems by fluorescent materials, and plant fluorescence. This experiment was designed to test the ability of the FLD to detect plant water stress of mature citrus trees. The FLD provided indications of stress before visible signs appeared and was at least as sensitive as stomatal resistance and water potential measurements in evaluating stress. The FLD, mounted in an aircraft or on a space platform should be useful in detecting plant water stress over large areas.

14. Major Field Experiment

A wheat irrigation scheduling experiment (WISE) was conducted to determine if the stress-degree-day (SDD) concept could be used to schedule irrigations for wheat grown on a commercially-operated farm. Since we had demonstrated that we could use an accumulation of ten positive stress-degree-days (Σ SDD+) as the optimum value by which to irrigate wheat in small experimental plots (0.05 acre) at our laboratory, we felt it necessary to try the technique on larger areas (3-12 acre borders) on a commercial farm. We found such a farm in Tacna, Arizona upon which we were allowed to irrigate eight borders of approximately 3.5 acres each on a fine sandy loam soil (F), and six borders of approximately 12.5 acres each on a silty clay soil (C).

The study was a cooperative venture between the U. S. Bureau of Reclamation (Irrigation Management Service), Sun Harvest, Inc. and our Laboratory. Since the USBR was already scheduling irrigations in the Wellton-Mohawk Valley using the neutron probe, they were interested in determining if our proposed technique could help them improve their system. They assigned two technicians to the project: one to be assigned full time to collect the data, assist in its analysis, irrigate the borders as required, and coordinate our activities with those of the cooperator, and the other to act as a backup when needed. Our responsibility was to set up the experiment, train the technicians, analyze the data and determine when each border needed water according to the various irrigation treatments. The cooperator was to provide water as required and to perform normal cultural practices.

Yecora wheat was planted on 08 January 1979 in the fine sandy loam soil and on 14 February 1979 in the silty clay soil.

Six irrigation treatments were established for comparison with the usual farm irrigation schedule. Wheat yield for each border was also taken for comparitive purposes. The irrigation treatments were:

1) Irrigate when there was an accumulation of +5 SDD.

2) Irrigate when there was an accumulation of +10 SDD.

3) Irrigate when there was an accumulation of +15 SDD.

4) Irrigate when there was an accumulation of +20 SDD.

5) Irrigate when the water content in the top foot of the soil had reached the "refill point" as specified by the USBR.

6) Irrigate when 65 percent of the available water was depleted from the top three feet of the root zone.

We also monitored a border that the cooperator irrigated by his schedule (experience).

Two measurement sites in each border were set midway between the side berms, one-third the distance from each end. At each site during the entire growing season we measured canopy temperature with an infrared thermometer between 1230 and 1330 hours, Monday through Friday, and soil water contents with a neutron moisture meter every 20 cm from 20 through 160 cm on Monday, Wednesday, and Friday. Daily measurements at the time of canopy temperature measurements were taken of the wet and dry bulb temperatures at both the fine- and coarse-textured soil plots. Incoming solar radiation, maximum and minimum air temperatures and wind run were taken daily, and charts from a recording hygrothermograph were gathered weekly. Six plants were removed randomly from each site each Tuesday for analysis of green leaf area, growth stage, and dry matter production. This body of data was voice-transmitted from Tacna to our laboratory five days a week, and the data was typed into the computer for immediate reduction and analysis. With such a set-up we were hoping to approach a real-time situation whereby canopy temperatures would be measured in the field and a decision would be made that same afternoon whether or not to irrigate.

Results and Conclusions

Because of the later planting date on the fine soil (F) and two unauthorized irrigations on five of the plots, the plants were unable to develop much stress, so this discussion will deal with the coarse soil (C) plots.

The amounts of water applied (irrigations and rain) to each plot and the dates are tabulated in Table 1. Plot 6 is the deviant of the group. The probable reason for its behavior is that the soil in this plot was of a much finer texture and consequently, a higher available water holding capacity than any of the other plots. Because of this, there was a period around the time of heading that the crop was being stressed due to the gradual reduction in soil water content, thereby causing a final yield reduction.

The general sandy nature of the soil in the other plots meant that water was needed frequently to maintain adequate soil moisture. This condition resulted in a rather overall low irrigation efficiency as compared to finer textured soils.

Although each plot was irrigated as a whole, the east half of the plots generally tended to be cooler than the west half. The first four plots accumulated fewer positive stress-degree-days and had higher yields at the east sites as compared to the west sites, Table 2. In plot 5 the east site was very slightly cooler, had a lower plant population, and also a lower yield than the west site. The reversal of the accumulation of positive stress-degree-days and yield for plot 5 as compared to the first four plots is not known. Since the soils throughout this area are quite variable and since there were no replicates of treatments for comparison purposes, we may be seeing a plant stress induced by some soil parameter. There is not enough field information to answer the question.

Plot 6 was originally set up to accumulate 20 positive stress-degree-days before irrigating it. As previously mentioned, the soil in this plot was finer textured than the others' and plant stress never progressed as we thought it would. The plot (7) irrigated by the farmer's usual method had a total of seven irrigations, had the efficiency (44%). It should be noted that the east sides of plots 1 and 2 (six irrigations each) actually out yielded plot 7 (594 g/m^2 versus 558 g/m^2), indicating that the farmer may indeed be over irrigating. There appeared to be essentially no soil or plant difference between the east and west sides of plot 7.

Based on the data given in Table 2, we are unable to verify that an accumulation of ten positive stress-degree-days between irrigations indicates the proper time to irrigate wheat. Possible explanations for the nonverification of our model are:

1) The rate of accumulation of SDD+ may affect the total number of SDD+ needed for irrigation. Plants on a sandy soil (as in Tacna) will accumulate SDD+ faster than those grown on a clay loam soil (as in our experimental plots where the concept was developed).

2) SDD+'s accumulated faster than we anticipated and we were unable to get irrigation water when we needed it due to ordering procedures. This resulted in higher values of SDD+ to accumulate than we really wanted.

3) There was enough soil variability in most of the plots that if we used the west site to schedule irrigations, the east site was not stressed, and if the east site was used as the norm, the west site would have been overstressed. In any case, we must devise better ways to monitor canopy temperature in the field so as to make rational decisions of when to irrigate.

SUMMARY AND CONCLUSIONS:

Several separate experiments were conducted to characterize the spectral and thermal properties of small grains. A brief description of the results of these experiments follows.

A single equation was developed to calculate daily evaporation rates during the three stages of soil drying. The only required input data are daily incoming and reflected solar radiation and maximum and minimum air and soil surface temperatures.

An intensive 23-day airborne and ground measurement program compared airborne acquired wheat canopy temperatures with simultaneous ground measurements. For canopies that covered at least 85 percent of the soil surface, airborne measurements differed from ground measurements of plant temperature by less than 2°C. This appears adequate for airborne implementation of the stress-degree-day concept. For less than 85 percent cover, the difference may be too great to be ignored. Thus, the relationship between the mean temperature of a field, as sensed by an infrared thermometer looking directly downward, and the different temperatures of the component plant and soil layers that make up the composite signal was examined. Also, the variation in crop temperature that results from viewing a crop canopy from a variety of different angles from the zenith was determined. These results point out the importance of determining an optimum view angle to obtain a true crop canopy temperature. The results have important implications for optimizing sensor view angles for remote sensing missions. The theory and measurements document that remote measurements of vegetation canopy temperatures cannot be made indiscriminately over large spatial regions without consideration of the underlying physical principles.

A great diversity of crop data was pooled to develop a single predictive expression for crop yield, based primarily on measurements of crop canopy temperature. This one relationship has been found to be applicable to sorghum, soybeans, red kidney beans, alfalfa, barley, and two varieties of wheat, some of which crops were grown in three different locations and in three different years, with a variety of planting dates, seeding rates, and irrigation practices.

Radiometric canopy temperature measurements of wheat and alfalfa taken at 1400 hours on clear days at Phoenix, Arizona, were used together with concurrent air temperature and vapor pressure data to develop a procedure for adjusting conventional stress-degree-days (1400-hour canopy-air temperature differentials) for climatic variability, represented by air temperature and vapor pressure variability. This normalization procedure effectively redefines the stress-degree-day parameter, equating it with the difference between the actual measured value of the canopy-air temperature differential and the value that would have prevailed for the day's particular air temperature and vapor pressure conditions, had the crop been well watered.

Experiments relating surface-air temperature differentials ($T_S - T_A$) of open water, bare soil, and crop canopies to air vapor pressure deficit ($e_A^* - e_A$) and net radiant heat load (R_N) showed that for open water and potentially evaporating bare soil, there is no unique relationship of the form $T_S - T_A = a + b\,(e_A^* - e_A)$ that is independent of R_N. For plant canopies, however, such a relationship does exist; and it appears to be a definitive criterion for the existence of a potential evaporation state.

As an aid in the interpretation of remotely sensed data from row crops with incomplete canopies, a model was developed that allowed the calculation of the fractions of sunlit soil, shaded soil, sunlit vegetation, and shaded vegetation for each resolution element in a scan of a remote sensor for a given set of conditions (plant cover, plant height/width ratio, row spacing, row orientation, time of day, day of year, latitude, and size of resolution element). With composite reflectances and temperatures known as a function of view angle, ways were explored to extract plant cover and plant temperature data from the composite data. Experimental data and theoretical calculations showed that spectral reflectances and two vegetation indices calculated from reflectances of row-planted crops varied up to one-half the total possible range of values during the course of a day. This variability was due to changing shade conditions which markedly alter the reflectance properties of a composite soil and plant scene. It was concluded that crop configuration is a major determinant of spectral reflectance, probably sufficient to obscure varietal differences, and should be accounted for in the interpretation of multidate imagery.

Spectral reflectances were used to develop a grain yield model. During the period of grain filling, yields of two wheat and one barley varieties were well correlated with the integrated daily values of a modified vegetation index derived from reflectances in MSS Bands 5 and 7. The model accounted for 88 percent of the variability in yields which were due to differential experimental soil moisture conditions.

A Fraunhofer Line Discriminator was used to detect plant water stress of mature citrus trees. The FLD provided indications of stress before visible signs appeared and was at least as sensitive as stomatal resistance and water potential measurements in evaluating stress.

A wheat irrigation scheduling experiment was conducted to determine if the stress-degree-day concept could be used to schedule irrigations for wheat grown on a commercially operated farm. Because of the great soil variability within the six experimental plots and the difficulty of scheduling water deliveries from the irrigation district, we were not able to verify that the accumulation of ten positive stress-degree-days was the proper indicator of when wheat needed to be irrigated.

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

Table 1. Dates and amounts (cm) of irrigation water applied and rainfall on coarse soil plots.

Julian Day	Rain	Plot 1 (65% use)	Plot 2 (User)	Plot 3 SDD=5	Plot 4 SDD=10	Plot 5 SDD=15	Plot 6 SDD=20	Plot 7 Farmer	Remarks
341		29.2	29.2	29.2	29.2	29.2	29.2	29.2	Preplant Irrigation
8									Planting
16	1.0								Rain
18	0.5								Rain
25	1.0								Rain
26	0.8								Rain
28	0.1								Rain
31	0.1								Rain
51		16.5	16.5	16.5	16.5	16.5	16.5		Irrigation & Full Canopy Cover
55								20.1	Irrigation
60	1.1								Rain
74		16.5	16.5					16.5	Irrigation
77	0.1								Rain
78	2.7								Rain
79	0.8								Rain
87	0.5								Rain
98		13.5	13.5	13.5	13.5	13.5		13.5	Irrigation
100									Heading
116		14.7	14.2	15.2			16.5	19.1	Irrigation
122					15.2	16.3		16.8	Irrigation
130		16.5	16.5	16.5					Irrigation
131								19.1	Irrigation
135					12.4	12.4			Irrigation
139	1.9								Rain
145									Scenesence
Total	13.6	106.9	106.4	90.9	86.8	87.9	62.2	134.3	
Consumptive Use	65.5								
Irrig. Efficiency		61	62	72	75	75	105	49	(%)
Overall Efficiency		54	55	63	65	65	86	44	(includes rain)
Final Yield		475	440	226	190	189	381	558	(g/m^2)

Table 2. Summation of positive stress-degree-days (deg. day) and soil water depletion (cm) in 170 cm soil depth for various irrigation cycles, plant densities (plants/m^2) and final wheat yields (g/m^2).

Plot	Irrigation Cycle Julian Day From	To	West Side Deg. Day	West Side cm water	West Side Yield(g/m^2) / Plant/m^2	East Side Deg. Day	East Side cm water	East Side Yield(g/m^2) / Plant/m^2	Average Deg. Day	Average cm water	Average Yield(g/m^2) / Plant/m^2
1											
65%	51	74	0.8	12.5		0	6.7		0.4	9.6	
available	74	98	4.6	19.8	279/241	0	12.8	672/323	2.3	16.3	475/282
water use	98	116	16.0	12.1		0	2.5		8.0	7.3	
	116	130	12.2	8.3		0	6.5		6.1	7.4	
2											
U.S.B.R.	51	74	0	12.1		0	16.7		0	14.4	
method	74	98	0.3	15.5	364/276	0	24.0	516/296	0.2	19.8	440/286
	98	116	6.4	19.8		0	17.1		3.2	18.5	
	116	130	7.2	5.7		0	9.0		3.6	7.4	
3											
SDD=5	51	98	13.7	23.5	182/267	3.5	21.3	271/316	8.6	22.4	226/291
	98	116	11.3	15.0		2.0	8.7		6.6	11.8	
	116	130	14.0	7.9		0.2	6.3		7.1	7.1	
4											
SDD=10	51	98	15.7	23.9	122/250	1.6	21.0	258/313	8.6	22.4	190/282
	98	122	23.5	10.5		6.9	12.0		15.2	11.2	
	122	135	22.9	2.9		17.1	5.0		20.0	4.0	
5											
SDD=15	51	98	15.4	24.2	198/331	12.1	24.4	180/275	13.8	24.3	189/303
	98	122	29.0	9.6		24.4	12.4		26.7	11.0	
	122	135	29.9	5.9		27.5	11.4		28.7	8.6	
6											
SDD=20	51	116	16.9	14.3	435/267	17.4	21.1	327/301	17.2	17.7	381/284
7											
Farmer	57	74	0	15.7		0	11.9		0	13.8	
method	74	98	0	19.5		0	20.6		0	20.0	
	98	110	0	8.3	554/406	0	8.7	562/417	0	8.5	558/412
	110	122	0	13.2		0	7.4		0	10.3	
	122	131	0	8.5		0	9.9		0	9.2	

TITLE: COMPUTER SIMULATION OF GREENHOUSES

NRP: 20760 CRIS WORK UNIT: 5510-20760-001

SUMMARY AND CONCLUSIONS:

An additional subroutine for modeling wet or dry air to water heat exchangers was written for the "modular energy balance" (MEB) program. As described in previous Annual Reports, each module or subroutine simulates the performance of some energy-related device. Patterned after a TRNSYS program from the University of Wisconsin, the modular energy balance program is highly versatile because the user specifies at run time which of the devices he wishes to include in a particular run and how they are connected (wires and pipes) together. The program has virtually no size limit as implemented on the USWCL mini-computer because the subroutines are stored on the disk as overlay modules.

Much effort was expended in 1979 writing a users' manual for the MEB program. The 200+ page manuscript is entitled, "A Modular Energy Balance Program Including Subroutines for Greenhouses and Other Latent Heat Devices," and it will be published in the U. S. Department of Agriculture, Science and Education Administration, Agricultural Review and Manual (ARM) series. Each subroutine model is described in detail, and program listings and instructions for use are included. A draft of the initial version of the manual has been completed, and examples for each subroutine model are now being run with a standardized set of input data. The manuscript should begin the review process shortly.

Also during 1979, a magnetic tape containing the WBAN Hourly Surface Observations 144 for Phoenix 1969-1978 were purchased from the National Climatic Center. These data were then processed with the DECODER program described in the 1976 Annual Report. This program converts to SI units and simulates solar and sky radiation as well as interpolating data every 0.5 hr. from the observations taken every 3 hr. These data will be averaged and used in simulations of the annual performance of greenhouse heating and cooling systems.

PERSONNEL: B. A. Kimball

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

NRP: 20760 CRIS WORK UNIT: 5510-20760-001

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.

Spring 1979 'Tropic' Tomato Crop

During 1979 an additional spring crop of tomatoes was grown to satisfy Objective 3. Environmental data was recorded as reported in past years. The yields from this crop, as well as those of the previous fall 1978 'N-65' tomato crop, are presented and analyzed in detail in a manuscript, "Spring and fall tomato yields with CO_2-enrichment in unventilated and conventional greenhouses." The ventilated, ambient CO_2 control greenhouse had marketable fruit yields of 6.19 and 10.4 kg/plant for the fall and spring crops, respectively. For the fall crop, there was no significant difference in yield in the unventilated, CO_2enriched greenhouses. For the spring crop, there was little difference in marketable fruit yield among the greenhouses. However, CO_2-enrichment stimulated the production of larger fruits, many of which were catfaced, so the total fruit yield was 20% higher in the unventilated, CO_2-enriched greenhouses and 5% higher in a ventilated, CO_2-enriched greenhouse. There was no significant yield difference between an unventilated greenhouse enriched to 1000 $\mu\ell$ CO_2/liter and another enriched to 1350 $\mu\ell$ CO_2/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.

These record high yields again confirm the great yield potential of CO_2-enriched, unventilated greenhouses. The lower quality of the larger fruits, however, means that improved variety selection or development is required before the potential can be marketed.

The yields from all of the greenhouses of 8-12 kg/plant have been higher than the 3-7 kg/plant generally reported by other researchers. One possible reason for the exceptional yields is that the greenhouses are relatively small and have a large "oasis" effect. The fact that the yields from all the plants were weighed individually for the spring 1979 crop provided data to test the magnitude of the effect. In Table 1 the means of individual rows of plants are presented. Rows 1 and 5 are outside rows and the aisle is between rows 2 and 3. For both marketable and total yield, row 1 significantly outyielded row 2, and row 5 significantly outyielded row 4. Focusing on the total yield, the outside rows outyielded the inside by about 10%. Because about half of the plants in each greenhouse are on the outside, the magnitude of the oasis effect is about 5%. This is relatively small compared to the magnitude of the difference between our yields and those of others, so the oasis effect is only a small part of the reason we have had higher yields.

The CO_2, energy, and water consumption were also recorded and these data are presented in Tables 2-5. The kg CO_2 supplied per plant as natural gas is presented in Table 2. Also presented are the percentages of CO_2 supplied that were recovered in the dry matter of each plant. About 20% of the CO_2 was recovered in the unventilated greenhouses, which is close to the values from the previous spring crop reported in the 1977 Annual Report.

The length of time per month that the heating, cooling, and emergency ventilation systems were in operation is listed in Table 3. Again, differences in sealing are apparent as indicated by the greater time of heater operation in greenhouse 2. Using the operating times in Table 3 and the power ratings in Table 4, the monthly energy use per plant for heating and cooling was calculated, and these results are presented in Table 4. The results indicate the unventilated greenhouses used about six times as much energy for cooling as the ventilated houses. This factor is about twice as large as reported in the 1977-78 Annual Reports and is larger than that dictated by the physics of heat transfer. At any rate, the fact that the cooling tower cooling systems have an additional fan in the cooling tower and two pumps for circulating water means that more energy is required for operation than for the conventional systems. Therefore, as will be discussed later in more detail, the emphasis of the project is shifting toward energy conservation (Objectives 1 and 2) and away from yield evaluation (Objective 3), which we now feel has been accomplished for tomatoes.

The amounts of water lost from the cooling and irrigation systems are listed in Table 5. These results also are similar to those reported in the 1977-78 Annual Reports. The evapotranspiration from the unventilated houses was about 150 ℓ/plant compared to 250 ℓ/plant from the ventilated houses. The water consumed by the cooling systems was about 740 and 1930 ℓ/plant in the ventilated and unventilated greenhouses, respectively, so the total water use was about double for the unventilated houses with cooling towers. While the higher yields attained in the unventilated houses can justify this greater water use, there is greater potential for practical application if the cooling system was more conservative. Thus the emphasis of the research has shifted toward the study of water (and energy as mentioned above) conserving cooling systems and away from yield studies.

Flavor and Vitamin A and C

The flavor of the tomatoes from the 1977-78 winter crop of 'Tropic' tomatoes was tested using sensory panels as reported in the 1978 Annual Report. Also sample tomatoes from the fall 1978 'N-65' crop and the spring 1979 'Tropic' crop were frozen and sent to the Western Regional Research Center, Berkeley, California, for vitamin A and C analyses. The results of these studies are reported in the manuscript, "Effects of CO_2-enrichment, ventilation, and nutrient concentration on the flavor and vitamin content of tomatoes.

The results showed that CO_2-enrichment to 1000 μℓ/ℓ of conventional ventilated greenhouses had no significant effect on the flavor panelists' scores. The scores from the unventilated greenhouses were significantly lower, but the decrease was small compared to the much lower scores for market field tomatoes. High nutrient concentration significantly improved the scores.

Neither CO_2-enrichment, ventilation, nor nutrient concentration had any consistent effect on vitamin C content. On the other hand, vitamin A content was increased with CO_2-enrichment and lack of ventilation, but nutrient concentration had no effect.

Thus, we conclude that CO_2-enrichment of tomatoes in ventilated greenhouses should continue as standard horticultural practice because it improves yield and nutritional value without affecting taste. We also conclude that the decision to use or not to use CO_2-enriched, unventilated greenhouses should depend almost entirely on yields and costs because the human factor of slightly impaired taste is offset by slightly improved nutritional value.

Greenhouse Temperature, Leaf Resistance, Air Resistance, and Leaf Area Study

On 7 June 1979 an intensive diurnal study was conducted. The objective was to obtain experimental data needed for the computer modeling effort. In particular these data included: 1. temperature of the outside cover, inside cover, vegetation, soil surface, and inside air and also inside air humidity ratio, which are the variables predicted by the Type 14 Complicated Greenhouse model; 2. the leaf resistance of tomato leaves as affected by solar radiation intensity and CO_2-enrichment; 3. the inside air resistance or heat transfer coefficient from tomato leaves; and 4. the leaf area determined from individual leaf and from row measurements.

Starting before dawn at 0530, measurements were taken hourly until 2030 after sunset. The data acquisition system was operated in an averaging mode with printouts every hour on the hour, so the manual observations were obtained near the middle of the averaging period of the data acquisition system. The sky was clear except near 1500 when a few clouds appeared for a couple of hours. All measurements were taken on both the ambient-CO_2, ventilated greenhouse 2 and on 1000 $\mu\ell/\ell$ CO_2, unventilated greenhouse 3. The cooling thermostats were adjusted so that the cooling systems were off from 0400 to 0800, on part of the time from 0800 to 0900, on continuously from 0900 to 1900, and on part of the time from 1900 to 1915, and off from 1915 to 2100.

Surface temperatures were measured with a Telatemp 1/ infrared thermometer. The observations were spoken into a voice recorder and then transcribed onto data sheets at the end of each hourly observation period. First the upper cover temperatures of the west side of the roof of greenhouse 2 and the east side of greenhouse 3 were measured from atop a tall stepladder. Then outer cover temperatures chest high on the south wall on the east and west side of greenhouse 2 were obtained. Then the inside cover temperatures of greenhouse 2 were obtained from the roof on the east and west sides and from the south wall on the east and west sides. A vegetation temperature from both east and west sides was taken at about chest height from a distance of 2-3 meters and included both sunlit and shaded leaves. A soil surface temperature also was obtained from both east and west sides. The sand "soil" appeared mostly moist with patches of dry, particularly in greenhouse 2. The soil surface temperatures were taken near the middle of the east and west beds.

Leaf resistances were measured each hour with a Lambda resistance meter of the vertical cylinder type. Duplicate measurements were taken on east and west sides of the greenhouses on both upper and lower leaf surfaces and on both sun and shade leaves. Horizontal solar radiation intensity was also measured each hour with a Spectran radiometer in the sun and in the shade close to the leaves where the resistance measurements were taken. Carbon dioxide concentration and air dry- and wet-bulb temperatures were monitored with the data acquisition system.

1/ Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the listed product by the author or the U. S. Department of Agriculture.

Air resistance was determined using simulated tomato plants constructed with leaves of green blotter paper. The "leaves" were hung from piano wire petioles on four sides of a 2 x 2 cm wooden stem. The plants were 2 m tall and had 10 leaves cut to resemble the size and shape of tomato leaves. The plant leaves were wetted and then the weight loss of the plants was measured with a balance accurate to 0.1 g. One plant each was used in greenhouses 2 and 3. The artificial plants were inserted in gaps between the actual tomato plants near the middle of the west beds.

The temperature data are presented in Tables 5 and 6 and Figures 1 and 2. There is little that is special about these numbers themselves. However, they are now available for comparisons with values predicted by the computer models. The outside weather data are in Table 1 and show that 7 June 1979 was a typical sunny June day for Phoenix. The inside greenhouse data are in Table 6. At midday the cover temperatures were about 10°C warmer than inside air temperatures. The vegetation temperatures were generally quite close to the inside air temperatures in greenhouse 2, whereas the blotter leaf temperatures were about 2°C cooler, as illustrated in Figure 1. In greenhouse 3, however, the vegetation and blotter temperatures were about 2-3°C warmer than the air temperatures. If the radiation properties of the real and blotter leaves were the same, these temperatures indicate that the blotter leaves were evaporating more rapidly than the real leaves in greenhouse 2 but at about the same rate in greenhouse 3.

The leaf resistance data are plotted in Figure 3 against the solar radiation intensity measured at the same time close to the subject leaf. The data appear reasonable with high resistances of 6 to 70 s/cm at zero radiation decreasing rapidly as the stomates open to about 4 s/cm at 100 W/m^2 and then decreasing slowly to about 1.5 s/cm at 750 W/m^2. Comparing the different symbols in Figure 3, the only group that appears any different from the rest are the lower surfaces of the shade leaves in greenhouse 3, which had resistances about 2 s/cm lower than the other leaves at the same low light intensities. Except for these lower-shade-GH3 leaves at the same light intensity, there was little difference between the upper and lower leaf surfaces, and there also was little difference between the leaves from greenhouse 2 and greenhouse 3. The latter observation means that the higher CO_2 concentration and humidity in greenhouse 3 did not noticeably affect stomatal behavior.

The resistances of the upper and lower leaf surfaces were added in parallel, and then these resultant resistances were averaged for the east and west sides of the greenhouses. Then these averaged parallel resistances were plotted in Figure 4 against the solar radiation averaged for the east and west sides. Sunlit and shade categories were kept separate. The averaging considerably reduced the scatter in Figure 4 as compared to Figure 3.

Only Hicklenton and Jolliffe (1978) have reported measurements of the leaf resistance of tomatoes in the literature so far as we know, and their data and Figure 4 agree fairly well, particularly for higher radiation levels. However, they found higher CO_2 concentration increased the leaf resistance at radiation levels that corresponded to about 100 W/m^2 of solar, while here the higher CO_2 concentration (or the higher humidity) appears to have slightly decreased the resistance. The curve in Figure 4 was fitted to the data by eye.

The form chosen for the equation is the same as used previously for the computer model (Kimball, 1973), and the constants in the equation will be used in the model in future simulations.

The results of the air resistance determinations are presented in Table 8. The heat transfer coefficient values are fairly high, more typical of forced convection than natural convection (Kimball, 1973). The air resistance, r_a, was computed from the evaporation rate, E, the total blotter leaf area, A, and the difference between the saturation humidity ratio of the blotter leaf, W_v*, and the humidity ratio of the inside air, W_{ai}.

$$r_a = A(W_v* - W_{ai})/E \qquad (1)$$

Then the heat transfer coefficients were calculated by dividing the moist air heat capacity (1035 J/kg·C) by the air resistances. The heat transfer coefficients were fairly high, averaging 19 $W/m^2 \cdot C$ for greenhouse 2 when the cooling system fan was on. These values are more typical of forced than natural convection (Kimball, 1973). The values for greenhouse 3 were about half those from greenhouse 2 for an unknown reason. The "plants" were both in the same relative position in the greenhouse with nearly the same air velocities. Possibly the humidity gradients were most in error, and more temperature measurements of more blotter leaves should have been made. Also the psychrometers for measuring air dry- and wet-bulb temperatures should have had fresh wicks and have been placed closer to the artificial plants. When the cooling systems of both greenhouses were off, and the air velocities in both greenhouses decreased, the heat transfer coefficients also decreased to about 60% of their previous values.

The leaf area measurements are presented in Table 9. The individual leaf measurements were obtained by counting the number of leaves on every plant in greenhouse 2 and 3 on 7 June 1979. Then when the final harvest was completed on 21 June 1979, the area per leaf of about 24 "lower" and "upper" leaves was measured on a Lambda area meter. The leaf area index for greenhouse 2 was 2.1 compared to 1.7 for greenhouse 3. This difference is consistent with our subjective observation that the vegetation was more lush in greenhouse 2. The gross row measurements were obtained by imagining the rows to be hedges and then measuring the height, length, and width of the row. This method yielded 2.8 and 2.7 for the leaf area indexes in greenhouses 2 and 3, respectively. These values are 1.33 and 1.59 times larger than the individual leaf values. Even though the row method is in error, it is very simple and nondestructive, so further comparisons and calibrations should be made.

Guayule

After the tomato crop was harvested, emphasis of the project shifted toward design and testing of energy and water conservation devices with much of the work being done on greenhouse 4. This left greenhouses 1, 2, and 3 available for a cooperative study with Dr. Ralph Backhaus, Arizona State University, on the effects of CO_2 enrichment on growth of Guayule seedlings and on rubber production in mature plants. Therefore, a fall crop of Guayule with several shorter seeding experiments was grown in the three greenhouses. Preliminary analysis of the results indicated that the fresh weight of the plants grown in the 1350 $\mu\ell$ CO_2/ℓ, unventilated greenhouse 3 was 50% greater than that from plants grown in the ambient CO_2, ventilated greenhouse 2.

Soil Temperature

Largely in response to numerous local requests for soil temperature data in the Phoenix area, the soil temperature measurements were continued through 1979, except when the data acquisition system was off in June and July for crop change in the greenhouses. The temperatures are presented in Figures 5 and 6 and summarized in Table 10. At the 0.25-m depth, the temperature ranged from 9.0°C on 1 February to 37.8°C on 10 August. The temperature was considerably damped at the 2.5-m depth, where it ranged from 18.8°C on 20 March to 26.8°C on 20 October. Thermal diffusivities were computed from the amplitude ratios for adjacent depths and averaged 0.33 mm^2/s.

Thermal Energy Storage

As mentioned previously, an important objective of this project is the evaluation of methods of thermal energy storage as a means to achieve wintertime heating and summertime cooling. Calculations have shown that in a climate like that of Phoenix there is enough excess solar energy received during daytime, on the average, to heat the greenhouse at night, if this energy could be stored. The greenhouse is its own solar collector. In cooler climates external solar collectors can provide additional energy for nighttime heating if storage is available. The collection of excess energy during the daytime cools the greenhouse, which reduces the ventilation or cooling requirements. Such unventilated greenhouses use less water, and they can be enriched with CO_2 to increase yields 20-50%, as we discussed earlier. Once a greenhouse is equipped with a thermal energy storage device, additional nighttime cooling techniques can be used to dump energy that is in excess of the greenhouse heating requirement. Such techniques include night sky radiation and nighttime evaporative cooling. The latter is more efficient at night because then wet-bulb temperatures are lower. Thus, the use of thermal energy storage offers many advantages.

The primary evaluation of thermal energy storage is planned to be accomplished by computer modeling. However, some performance evaluation of an actual system is required to assure the validity of the computer models. Among the materials commonly suggested for thermal energy storage are rocks, water, and heat of fusion salts. The rocks require the largest storage volume, and because air would be the heat transfer fluid, they are not very compatible with cooling devices such as evaporative cooling towers, night sky radiators, or fluid roofs. Water requires less volume than rocks and is compatible with the cooling devices, but it requires heat exchange with the greenhouse air. Heat of fusion salts offers the smallest volume, but commercial products with a melting point at about 22°C are not yet available. They are compatible with using the greenhouse air as the heat transfer media and also with using water because they could be placed in a water tank. Thus, a water system (possibly with heat of fusion salts), appears to offer the greatest hope of being practical, so a water system was selected for testing.

Installation was started in October of a large thermal-energy water storage tank. While choice of the optimum size of the tanks depends on the results of many future computer analyses of year-long operation, the size of the test tank was chosen on the basis of a bad case of summer cooling conditions. For 30 $MJ/m^2 \cdot day$ heat load and a greenhouse area of 28 m^2, the energy to be stored per day is 840 MJ. The maximum allowable dry bulb temperature in the greenhouse is 29.5°C and the average minimum wet bulb temperature outside is 18°C for a difference of 11.5°C. If one allows a 4°C temperature drop across the heat exchanger in the greenhouse and a 4°C approach of the water to the wet bulb temperature in a cooling tower, there is an allowable 3.5°C temperature change of the water. Then the volume of water required is:

$$V = \frac{840 \times 10^6 \text{ J}}{4190 \frac{\text{J}}{\text{kg}^\circ\text{C}} \cdot 3.5^\circ\text{C} \cdot 1000 \frac{\text{kg}}{\text{m}^3}} = 57 \text{ m}^3 = 15000 \text{ gal} \qquad (2)$$

Cost comparisons showed that a PVC-lined, galvanized steel grain storage bin like that of Dedrick and Lauritzen (1969) was the most economical storage. Therefore a 7.3-m (24-ft) diameter, 1.70-m high

(5.5-ft) bottomless bin with conical galvanized steel roof and a 9.1-m^2, 0.76-mm-thick PVC liner was purchased. A hole was excavated north of greenhouse 4 and the bottom was leveled. The steel rings were erected at an elevation about 46 cm below the drain pan of the spray chamber in greenhouse 4 to provide gravity return flow. Thermocouples and soil heat flux plates were installed in the soil under the tank at the positions shown in Fig. 7. Then about 5 cm of sand was placed over the soil in the bottom and the PVC liner was installed using slitted PVC tubing to clip the liner to the top of the tank without damage, as described by Dedrick and Lauritzen (1969). A first liner leaked at some of the seams, but was replaced by the manufacturer. A second is holding water nicely. Then the roof was installed. At year's end, plumbing of intakes to and drains from greenhouse 4 and cooling tower 4 was being done prior to spraying the sides and roof of the tank with polyurethane insulation and then backfilling around the sides. Figure 4 shows the planned installation of additional thermocouples and heat flux plates and the insulation.

Fluid Roofs

Solar radiation consists of about half visible radiation which plants use for photosynthesis and half nearinfrared radiation. Because the plants do not use the nearinfrared radiation for photosynthesis, it represents an unnecessary heat load on the plants. For many years, plant physiologists have used water or solutions of $CuCl_2$, $CuSO_4$, or $Fe(NH_4)_2 (SO_4)_2$ in filters above their plants to remove nearinfrared radiation before it reached their plants (Withrow and Withrow, 1956). The possibility for selectively removing near infrared radiation with a special greenhouse roof was included as one option in our original computer model (Kimball, 1973). The first full-scale greenhouse using the concept of a fluid roof was constructed in France by Damagnez (1976) and his associates using a double sheet of rigid plastic. More recently double-walled, hollow-channeled sheets of polycarbonate have become commercially available and Damagnez, as well as van Bavel and Sadler (1979), have begun testing this material. Van Bavel and Sadler have also been modeling the performance of fluid-roof greenhouses on a computer.

Such fluid-roof greenhouses may have particular application in the southwest where cooling is even more important than heating. Therefore, preliminary testing of double-wall polycarbonate sheets was initiated. The transmittance of polycarbonate alone and filled with water was measured with an Isco spectral radiometer, and these results are presented in Figure 8. The results show that the water, which was about 4 mm thick inside the polycarbonate, reduced the transmittance in the nearinfrared portion of the spectrum (> 750 mm) and slightly improved it in the visible portion (< 750 mm). For the nearinfrared, the transmittance averaged 0.78 with air and 0.56 with water, whereas in the visible it averaged 0.77 with air and 0.80 with water. The transmittance with various solutions, particularly $CuSO_4$ and $CuCl_2$, will be measured early next year.

Transmittance Deterioration of Fiberglass

During the past 3 or 5 years since the experimental greenhouses were erected, the fiberglass covering (Sunlite with tedlar) has yellowed noticeably. Therefore supplemental measurements were taken of the spectral transmittance of the roofs of three of the greenhouses and also of a sheet of the same material used for the roofs but which had not been exposed to solar radiation more than a few hours. The same Isco spectral radiometer was used for these measurements as was used for the polycarbonate fluid-roof measurements. The instrument was calibrated with a standard Isco iodine light source calibrator before and after taking the readings. The greenhouse measurements were taken with the leveled instrument on a step-ladder 96.5 cm below the roof panels near the north-south center of the greenhouse and about 1.5 m from the east wall. The unexposed sheet measurements were taken at about 45 cm below a sheet that curved up over some supports from the ground on the south.

The results are presented in Figure 9. They show that there has been a decrease in transmittance in the visible portion of the spectrum (< 700 nm), particularly in the blue and green which has caused the yellowing apparent to the eye. The average transmittance in the visible was 0.48, 0.45, and 0.52 for greenhouses 1, 2, and 3, respectively. Compared to the average in the visible of 0.73 for the unexposed sheet, there has been a deterioration of about 0.25 in transmittance of visible radiation. The average transmittances in the nearinfrared (> 700 nm) were 0.52, 0.54, 0.54, and 0.76 for greenhouses 1, 2, and 3 and the unexposed sheet, respectively, so the decrease was about 0.23. There was little difference between the curve for greenhouse 1, which was erected five years ago, and the curves for greenhouses 1 and 2, which were erected three years ago, so most of the change occurred within three years.

Vertical Curtain Heat Exchangers

The fans that circulate the air through the unventilated greenhouses and then through the aspen pad heat exchangers are relatively large consumers of energy. One possible way to eliminate this energy use is to substitute heat exchangers that rely on natural convection rather than forced convection to accomplish the heat exchange. Such natural convection heat exchangers have been constructed from plastic film vertical curtains, as described by Mears et al. (1977) and Simpkins et al. (1978) from Rutgers University.

The curtain heat exchangers built by the Rutgers group were for night-time heating. They were made from black plastic that would shade the plants if used for daytime cooling. We have instead tried a material that could be used for both daytime cooling and nighttime heating. The material was a 0.004-inch thick laminated film from Stauffer

Chemical. The film consisted of a layer of black vinyl, then aluminum, and then transparent polyester. When used as a curtain heat exchanger as shown in Figure 10, the black vinyl is placed inside, and the polyester outside. The film is highly reflective to solar radiation, so minimal shading of plants will occur; yet, the polyester has a high thermal emittance so heat exchange can occur by thermal radiation as well as convection.

Measurements were made of the reduction in solar radiation intensity caused by the vinyl-aluminum-polyester curtains. At 1345 on 21 September 1979 the solar radiation intensity at a height of 1 m (2 m high curtains) averaged 59% of the intensity above the curtains as determined by a Spectron solar radiometer.

We have made preliminary measurements of the heat transfer coefficients from vertical heat exchange curtains using the apparatus shown in Figure 10. The film was draped over 1 1/2-inch PVC pipes which served both as supports and as water-distribution systems. The pipes had two rows of 3/32-inch diameter holes drilled 2 inches apart along the top of the pipes. The water sprayed out of the holes and ran down the inside of the curtains. To improve the uniformity of the water flow down the inside of the curtains, the vinyl was treated with a wetting agent called Sun-Clear available from greenhouse supply companies. At least three applications of Sun-Clear were required before it spread and covered the vinyl surface. Then it markedly improved the wettability of the vinyl. The bottom of the curtains tucked into slots in 4-inch PVC pipes which served as gutters or drains.

The water used in the tests was cooled using the cooling towers. The absolute temperature of the inlet and outlet water was measured using single copper constantan thermocouples. The differential temperature between inlet and outlet, ΔT_W, was measured with a 10-pair thermopile. The water flow rate was determined by measuring the time required to fill a calibrated container. The average curtain temperature was taken to be the average of the inlet and outlet water temperatures. The air temperature was measured with the psychrometer connected to data acquisition system.

Heat transfer coefficients were computed from the data using the following equations. First the rates of heat removed from the greenhouse, Q (W), were computed from the water temperature change, ΔT_W(°C), and flow rate, F (kg/s)

$$Q = FC\Delta T_W \tag{3}$$

where C is the heat capacity of water, 4190 J/kg·C. Then the overall heat transfer coefficients, U(W/m^2·C), were computed from the area of curtain (counting both sides) and difference between the greenhouse air temperature, T_a(°C), and the average water temperature, T_w(°C).

$$U = \frac{Q}{A(T_a - T_w)} \qquad (4)$$

The results obtained so far are presented in Table 11. The case when the duct fan is off represents the planned mode of operation with minimal energy consumption. The lower, more conservative overall heat transfer coefficient (with the more accurately measured water temperature change) for this case was 6.9 $W/m^2 \cdot C$. This result means that for a bad case water temperature of 25°C, a maximum permissible air temperature of 32°C, and a heat load on the greenhouse of 700 W/m^2 of greenhouse floor that the required curtain area would be

$$A = \frac{700}{6.9(32 - 25)} = \frac{14.5 \text{ m}^2 \text{ of curtain}}{\text{m}^2 \text{ of greenhouse}} \qquad (5)$$

Our test greenhouses have 29 m^2 of floor area, so the required curtain area would be 420 m^2. The curtains shown in Figure 10 are slightly smaller than 6 m long and 2 m high and have an area of 22 m^2, so 19 curtains would be required. We have found that with just 5 such curtains (= 3.8 m^2 of curtain/m^2 of greenhouse) installed in one of the greenhouses that there is room for plants but little working space.

The condition chosen for this example is a bad but not worst case condition for August in Phoenix. Four alternative ways to improve the situation are being considered. First, use of the fluid roof already discussed could reduce the heat load inside the greenhouse by half. Second, use of a thermal energy storage tank presently being installed could extend cooling into nighttime which would be more efficient, and water temperatures closer to 18°C can be achieved. The combined use of a fluid roof with nighttime cooling would lower the required heat exchange area to 3.6 m^2 per m^2 of greenhouse. The roof would also be heat exchange area so the amount of curtain required would be about 2.6 m^2/m^2 which can be physically accommodated in a greenhouse. The third alternative is to switch operation to the present conventional techniques during the "monsoon" season from the middle of July to the end of August. During this time, Phoenix operators could shade their greenhouses and possibly use conventional evaporative cooling. Greenhouse maintenance, vacations, and crop changes could also be scheduled for this time. The fourth alternative is to operate the greenhouses at other locations than Phoenix. Devices which are impractical here because of the large scales involved may be economically attractive where slightly colder temperatures improve the efficiency of cooling. Evaluation of this fourth alternative is a job for the computer model discussed elsewhere.

The temperature of the curtain's polyester surface was measured at eight positions near the top, middle, and bottom at 1400 on 11 September 1979 using a Telatemp infrared thermometer. The average recorded was 29.4°C. Referring to Table 10, the average water temperature was 23.7 and greenhouse air temperature was 52.0. Therefore 20% of the temperature drop was across the water film and plastic and 80% was across the air film.

Next year we plan to make additional measurements of the heat transfer coefficient for such curtains. These additional measurements will be obtained at a range of airspeeds and also at a range of air to water temperature differences. These data will then be used in the computer model to predict the size requirements and performance of the curtain heat exchangers in a variety of applications.

SUMMARY AND CONCLUSIONS:

The yields of a spring crop of tropic tomatoes were determined in CO_2-enriched, unventilated and conventionally ventilated greenhouses. The ventilated, ambient CO_2 greenhouse had a marketable fruit yield of 10.4 kg/plant, and there was little difference in marketable fruit yield among the greenhouses. However, CO_2 enrichment stimulated the production of larger fruits, many of which were catfaced, and the total fruit yield was 20% higher in the unventilated, CO_2-enriched greenhouses and 5% higher in a ventilated, CO_2-enriched greenhouse. These record yields again confirm the high productivity of CO_2-enriched unventilated greenhouses, but also indicate a need for variety selection or development to obtain a variety that will put the extra yield into more marketable packages.

Tomatoes were also analyzed for their vitamin A and C content. The results showed that neither CO_2 enrichment nor ventilation had any consistent effect on vitamin C content. On the other hand, vitamin A content was increased with CO_2 enrichment and lack of ventilation.

Preliminary results from a fall Guayule crop, grown cooperatively with Arizona State University, showed a 50% increase in fresh weight from the CO_2-enriched, unventilated greenhouse over the ambient CO_2, ventilated greenhouse.

An intensive diurnal experiment was performed to obtain data for computer modeling. Surface temperatures of the outside cover; inside cover, vegetation, and soil were measured in CO_2-enriched, unventilated greenhouse 3 and ambient CO_2, ventilated greenhouse 2. Leaf resistance measurements were obtained in both greenhouses. The resistances were a function of solar radiation, but there was little or no difference between greenhouses or between the upper and lower surfaces of the leaves. Leaf areas were also determined, and air resistances were measured using wet blotter paper plants.

The emphasis of the project has shifted away from evaluating the yield response of plants in CO_2-enriched, unventilated greenhouses toward evaluating greenhouse systems and devices for conserving energy and water. This is mostly a computer modeling effort, but some experimental testing and verification is required. Central to most of the systems under consideration is a need for thermal energy storage, so a water tank was purchased and installation is in progress. Preliminary transmittance testing was also started on double-wall polycarbonate sheets. Greenhouse roofs could be made from these sheets filled with a fluid filter to remove the nearinfrared portion of the solar radiation before it enters the greenhouse. Plants do not use this energy for photosynthesis. Testing of vertical curtain heat exchangers were also done. Such curtains hang over water distribution pipes and exchange heat by natural convection with the air. They would conserve the energy normally consumed by the fans for forced convection exchangers. The results showed that the overall heat transfer coefficients were about 7 $W/m^2 \cdot C$, which implies that impractically large curtain areas would be required for some cases. Combined with thermal energy storage and fluid roofs, however, they may be practical, and further testing and modeling are planned.

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Table 1. Mean yields by row and greenhouse from the spring 1979 'Tropic' tomato crop.

GREEN-	STANDARD NUTR. CONC.			HIGH NUTR. CONC.		
HOUSE	ROW					
No.	1	2	3	4	5	mean
Mean marketable fruit yields (kg/plant)						
1	10.65 bcde	9.34 cdefgh	9.49 cdefg	8.66 fgh	10.66 bcde	9.76 BC
2	13.16 a	10.10 cdef	10.44 cdef	7.99 gh	10.41 cdef	10.42 AB
3	12.37 ab	10.97 bc	10.16 cdef	10.49 cdef	10.80 bcd	10.96 A
4	10.29 cdef	10.52 bcdef	7.57 h	8.05 gh	8.89 efgh	9.06 C
mean	11.62 A	10.23 B	9.42 BC	8.80 C	10.19 B	
% difference +	+ 14				+ 16	
LSD (5%) of an individual treatment mean = 1.87; of a row mean = 0.94; of a greenhouse mean = 0.84						
Mean total fruit yields (kg/plant)						
1	14.36 bcd	12.02 e	12.72 de	11.50 ef	12.78 de	12.68 C
2	14.72 bc	12.25 e	11.83 e	9.88 f	12.24 e	12.18 C
3	17.66 a	15.72 b	13.17 cde	14.33 bcd	14.87 bc	15.15 A
4	15.52 b	15.90 b	12.58 e	12.93 de	12.92 de	13.81 B
mean	15.57 A	13.97 B	12.58 CD	12.16 D	13.20 BC	
% difference	+ 11				+ 9	
LSD (5%) of an individual treatment mean = 1.74; of a row mean = 0.87; of a greenhouse mean = 0.78						

+ % difference is row 1 as a percent of row 2 or row 5 as a percent of row 4.

Table 2. CO_2 consumption and CO_2 recovery percentage in plant dry matter for 'Tropic' tomatoes, spring 1979, for the ventilated (V) and unventilated (U) greenhouses at various CO_2 enrichments.

Month	CO_2 supplied (kg/plant)			CO_2 recovered (% of supplied)		
Greenhouse No.:	1	3	4	1	3	4
Ventilation:	V	U	U	V	U	U
CO_2 (μℓ/ℓ):	1000	1000	1350	1000	1000	1350
Jan (12-31)	0.85	0.96	0.85	0.0	0.0	0.0
Feb	2.78	1.39	1.50	0.6	1.9	1.5
Mar	2.88	1.60	1.71	1.9	5.1	4.2
Apr	3.63	2.35	2.14	22.0	38.3	38.0
May	2.67	1.92	1.82	20.4	41.6	45.9
Jun (1-21)	3.52	2.99	2.14	24.0	33.7	41.6
Total:				Ave.:		
	16.33	11.21	10.16	15.0	20.1	21.9

Table 3. Monthly time of operation of heating, cooling, and emergency ventilation systems, 1979. Houses 1 and 2 were ventilated whenever their cooling systems were on, whereas houses 3 and 4 were ventilated only when the ridge vents were open.

	Greenhouse No. and Ventilation Type											
	1			2			3			4		
	Ventilated			Ventilated			Unventilated			Unventilated		
Month	heat	cool	vent	heat	cool	vent	heat	cool	vent	heat	cool	vent
	(hours)											
Jan (12-31)	138	2.9	--	214	1	--	203	8	0	173	6	2
Feb	162	15.3	--	251	8	--	187	42	0	122	36	0
Mar	89	18.0	--	164	12	--	113	60	0	102	64	0
Apr	50	41	--	159	30	--	48	133	0	57	217	4
May	5	105	--	25	166	--	6	251	2	5	244	6
June (1-21)	0	133	--	.3	166	--	0	255	10	0	239	17
Total for crop	444	315	--	814	383	--	557	749	12	459	806	29

Table 4. Energy consumption, 1979.

	Greenhouse No. and Ventilation Type							
	1		2		3		4	
	Ventilated		Ventilated		Unventilated		Unventilated	
Month	heating	cooling	heating	cooling	heating	cooling	heating	cooling
	(MJ/plant *)							
Power (kw):	6.85	1.47	6.85	1.29	6.85	3.39	6.85	3.65
Jan (12-31)	68	0	106	0	100	2	85	2
Feb	80	2	124	1	92	10	60	9
Mar	44	2	81	1	56	15	50	17
April	25	4	78	3	24	32	28	57
May	2	11	12	15	3	61	2	64
June (1-21)	0	14	0	15	0	62	0	62
Total crop	219	29	401	35	275	182	225	211

* MJ/plant = (hours) x (kw) x (3600 sec/hr) x $(1000 \frac{J/S}{kw})$ x $(10^{-6} \frac{MJ}{J})$/(50 Plants)

Table 5. Water consumed by the cooling systems, supplied to the plants by the irrigation system, and evapotranspired from soil and plants, 1979.

Month	Cooling Water			Avg. Irrigation Water	Evapotranspiration							
	Greenhouse No.				Greenhouse No. - Ventilation							
					1-V		2-V		3-U		4-U	
	1 & 2	3	4		S	H	S	H	S	H	S	H
	(ℓ/plant)											
Jan (12-31)	2	12	12	27	5	6	7	7	-	7	-	-
Feb	17	92	83	61	23	24	22	21	15	17	26	-
March	26	154	136	52	46	27	12	38	33	13	35	27
April	58	340	312	69	52	55	*	8	52	39	52	38
May	248	592	644	113	78	86	*	82	51	49	63	57
June (1-21)	388	744	740	59	51	44	*	17	29	22	34	27
Total for crop	739	1934	1927	381	255	242	-	173	-	147	-	-

*Water meter malfunction replaced August 1979.

Table 6. Outside weather data for 7 June 1979. The values are hourly averages except as noted. The times are the midpoints of the hours.

Time	Radiation Solar	Radiation Sky	Wind	Temperature Dry Bulb	Temperature Wet Bulb	Humidity Ratio	Barometric Pressure
	S_o	R_{ao}	U_{ao}	T_{ao}	T_{wb}	W_{ao}	P_{ao}
	W/m^2	W/m^2	m/s	C	C	g H_2O/kg air	kPa
0430	0	370	0.6	19.7	–	–	100.26+
0530	14	372	1.9	18.8	–	–	–
0630	156	378	2.4	20.9	–	–	–
0730	362	393	3.0	24.4	–	–	–
0830	581	399	3.5	28.2	–	–	–
0930	788	388	3.2	29.9	–	–	–
1030	957	371	3.4	32.0	18.6	7.95	–
1130	1047	374	3.4	33.3	–	–	–
1230	1073	373	3.1	34.5	–	–	–
1330	1016	394	2.3	34.9	–	–	100.30+
1430	887	430	2.0	35.8	–	6.63+	100.20+
1530	605	466	2.5	35.9	20.4	8.69	
1630	458	485	3.1	36.0	20.7	9.06	
1730	340	484	3.6	35.2	20.9	9.68	99.99+
1830	109	459	3.4	33.1	19.9	9.19	
1930	7	436	3.1	31.0	19.2	9.14	–
2030	0	414	3.4	29.3	18.4	8.82	–

+ As broadcast over weather radio from Sky Harbor International Airport.

Table 7. Greenhouse temperatures, humidity ratios, soil surface heat flux, and CO_2 concentrations on 7 June 1979.

	TEMPERATURES											
	outside		inside		average	vege-	soil	inside air		HUM.	SOIL HEAT	
								dry	wet			
TIME	roof[z]	wall[z]	roof[z]	wall[z]	cover[x]	tation[z]	surface[z]	bulb[y]	bulb[y]	RATIO	FLUX[y]	CO_2[y]
	(°C								)	g/kg	W/m^2	μℓ/ℓ
Ambient CO_2, ventilated greenhouse 2												
0430	14.3	17.2	16.0	17.4	16.2	18.4	20.5	19.6	18.3	12.8	10	566
0530	14.0	17.7	16.4	18.0	16.5	18.3	20.8	19.5	18.3	12.8	9	633
0630	16.7	19.8	20.0	20.4	19.2	21.6	22.8	22.2	20.9	15.2	-10	447
0730	18.0	23.1	22.8	23.8	21.9	24.4	25.2	26.0	20.9	13.5	-29	390
0830	21.2	25.8	24.2	25.8	24.2	22.6	27.7	25.6	18.8	10.9	-75	387
0930	24.4	28.8	29.6	28.2	27.8	22.8	30.4	24.4	18.9	11.5	-68	391
1030	27.2	32.0	32.6	31.4	30.8	23.3	30.6	24.1	20.0	13.1	-58	401
1130	30.4	34.0	34.1	33.0	32.9	24.2	33.0	24.5	20.6	13.8	-92	411
1230	32.0	35.8	35.8	34.2	34.4	25.2	32.9	24.6	20.6	13.7	-81	401
1330	30.2	34.6	34.7	33.4	33.2	25.4	30.1	24.9	20.8	13.9	-35	399
1430	30.2	36.0	34.3	33.4	33.5	25.0	32.8	25.3	20.8	13.7	-29	398
1530	29.8	34.8	32.4	32.5	32.4	23.8	31.8	25.0	20.6	13.6	-34	394
1630	33.9	35.4	34.4	33.2	34.2	25.8	31.4	25.0	20.6	13.6	-24	394
1730	31.2	34.9	33.6	32.5	33.0	25.8	30.9	24.3	20.5	13.7	-19	399
1830	27.6	31.4	29.4	30.2	29.6	24.1	27.5	24.1	19.5	12.4	-5	394
1930	25.4	28.8	26.7	28.6	27.4	25.7	26.9	25.9	20.6	13.2	-7	467
2030	24.0	27.9	25.5	26.4	26.0	25.4	26.2	26.4	20.7	13.1	-7	496
1000 μℓ/ℓ CO_2 unventilated greenhouse 3												
0430	15.1	18.0	17.4	18.4	17.2	19.5	22.0	20.6	19.7	14.2	9	2045
0530	15.0	18.1	17.8	18.6	17.4	19.4	21.9	20.4	19.5	14.0	9	2132
0630	18.6	20.2	21.4	20.9	20.3	22.8	23.8	22.9	21.7	16.0	-5	1717
0730	22.0	22.5	22.5	22.5	22.4	25.2	26.3	24.7	22.3	16.1	-23	896
0830	24.2	26.8	26.7	26.3	26.0	24.2	31.2	23.6	21.6	15.6	-43	933

Table 7. Greenhouse temperatures, humidity ratios, soil surface heat flux, and CO_2 concentrations on 7 June 1979 (continued).

	TEMPERATURES											
	outside		inside					inside air				
TIME	roof[z]	wall[z]	roof[z]	wall[z]	average cover[x]	vegetation[z]	soil surface[z]	dry bulb[y]	wet bulb[y]	HUM. RATIO	SOIL HEAT FLUX[y]	CO_2[y]
	(°C								)	g/kg	W/m^2	µℓ/ℓ
1000 µℓ/ℓ CO_2 unventilated greenhouse 3 (cont'd)												
0930	27.1	29.0	30.0	28.5	28.6	25.5	31.6	23.6	21.9	16.0	-47	857
1030	29.2	32.4	33.5	31.3	31.6	27.1	32.0	24.4	23.4	18.0	-48	832
1130	31.2	34.1	34.7	32.9	33.2	27.8	33.6	25.4	24.2	18.9	-53	791
1230	32.4	34.9	34.8	34.0	34.0	32.0	33.6	25.0	93 w	18.8	-61	864
1330	30.4	35.4	36.7	34.7	34.3	29.2	37.5	25.4	94 w	19.5	-57	976
1430	31.2	34.6	35.4	34.0	33.8	26.5	35.6	24.9	92 w	18.5	-51	1000
1530	29.8	35.8	33.0	32.7	32.8	27.2	33.5	25.0	91 w	18.4	-45	1026
1630	32.6	34.4	34.8	33.0	33.7	27.1	32.6	24.6	23.8	18.5	-22	963
1730	29.8	34.4	32.8	32.8	32.4	27.0	32.2	24.6	23.7	18.3	-16	988
1830	26.4	31.3	28.7	23.6	27.5	23.6	28.4	23.4	22.2	16.5	-3	967
1930	24.9	29.0	26.5	25.6	26.5	25.6	28.4	25.7	23.4	17.4	-3	737
2030	23.2	28.1	25.7	26.8	26.0	25.8	27.9	26.6	24.0	18.0	-6	791

z Manual observations taken within 5 minutes of the time listed. All values are averages of the west and east sides of the greenhouse except the outside roof values.

y Hourly averages from the data acquisition system. The times listed are the midpoints for the hours.

x Average of the first four columns.

w Wet bulb became dry. These values are the % relative humidity.

Table 8. Air resistance to mass transfer determined from weight loss of blotter paper "tomato" plants in ventilated greenhouse 2 and unventilated greenhouse 3. 7 June 1979.

TIME	BLOTTER temp	BLOTTER hum. ratio	AIR temperature dry bulb	AIR temperature wet bulb	AIR hum. ratio	HUM. RATIO DIFF	EVAP.	AREA	AIR RESISTANCE		HEAT TRANS. COEF.
	°C	g/kg	°C	°C	g/kg	g/kg	2/min	cm^2	$m^2 s/kg$	s/cm	$W/m^2 \cdot C$
Greenhouse 2 ventilated with cooling system on, circulation fan off[z]											
1200	22.9	17.8	24.5	20.6	13.8	4.0	2.45	5889	58	0.66	18
1300	22.6	17.5	24.6	20.6	13.7	3.8	2.06	5889	65	0.74	16
1400	23.2	18.2	24.9	20.8	13.9	4.3	2.88	5889	53	0.60	20
1500	22.3	17.2	25.3	20.8	13.7	3.5	1.91	5889	64	0.73	16
1600	21.7	16.5	25.0	20.6	13.6	2.9	2.44	6014	43	0.49	24
							Average		57	0.64	19
Greenhouse 2 cooling system off, circulation fan on											
1900	21.8	16.6	24.1	19.5	12.4	4.2	1.92	6014	79	0.90	13
Greenhouse 3 unventilated with duct fan on, circulation fan off[z]											
1200	27.3	23.4	25.1	24.2	18.9	4.5	1.60	5895	99	1.13	10.5
1300	27.8	24.1	25.0	93[y]	18.8	5.3	2.08	5895	90	1.03	11.5
1400	28.8	25.6	25.4	94[y]	19.5	6.1	1.71	5895	126	1.44	8.2
1500	27.1	23.1	24.9	92[y]	18.5	4.6	1.72	5895	95	1.08	10.9
1600	26.8	22.7	25.0	91[y]	18.4	4.3	1.30	6043	120	1.37	8.6
							Average		106	1.21	9.9
Greenhouse 3 unventilated with duct fan off, circulation fan on											
1900	24.8	20.0	23.4	22.2	16.5	3.5	0.66	6043	192	2.19	5.4

z Based on air flow rates of 3.75 and 3.44 m^3/s for greenhouses 2 and 3, respectively, and greenhouse cross-sectional areas of 12.0 m^2, the average air speeds were 0.31 and 0.29 m/s for greenhouses 2 and 3, respectively.

y Wet bulb became dry. These values are the percent relative humidity in unventilated greenhouse 4 at the same time.

Table 9. Leaf area in Greenhouse 2 and Greenhouse 3 on 7 June 1979 as determined by individual leaf measurements and by gross row measurements.

ITEM	GREENHOUSE 2	GREENHOUSE 3
Ventilation	ventilated	unventilated
Carbon dioxide concentration (μℓ/ℓ)	ambient	1000
Individual leaf data		
Number of leaves per plant	137.7 $\pm$ 2.1	13.3 $\pm$ 2.2
Total number of leaves for 50 plants	685	665
Area per leaf of "lower" leaves (cm^2/leaf)	1102 $\pm$ 302	866 $\pm$ 308
Area per leaf of "upper" leaves (cm^2/leaf)	321 $\pm$ 89	308 $\pm$ 70
Average area per leaf assuming 2/3 of leaves are "lower" (cm^2/leaf)	842	680
Total leaf area per plant (m^2/plant)	1.15	0.90
Total leaf area per 50 plants (m^2)	57.7	45.2
Leaf Area Index (for 27.3 m^2 soil area)	2.1	1.7
Gross vegetation row data		
Height to bottom leaves (m)	0.80	0.90
Distance from bottom to top leaves (m)	1.10	1.10
Row length (m)	5.0	5.0
Width of vegetation in row (m)	0.35	0.30
Gross area of parallelepiped (m^2/row)	15.3	14.7
Gross area of 5 rows (m^2)	76.4	73.5
Leaf Area Index (for 27.3 m^2 soil area)	2.8	2.7

Table 10. Summary of deep soil temperature data for bare Avondale loam in Phoenix, Arizona for 1979.

	MAXIMUM				MINIMUM		1979	
	1978		1979		1979		Max.	THERMAL
DEPTH	Temp.	Date	Temp.	Date	Temp.	Date	- Min.	DIFFUSIVITY [z]
m	C		C		C		C	mm^2/s
0.25	38	10 Aug	37.8	10 Aug	9.0	1 Feb	28.8	0.18
0.5	35	20 Aug	34.5	10 Aug	10.6	20 Jan	23.9	0.28
1.0	33	25 Aug	32.0	10 Aug	14.3	5 Feb	17.7	0.30
1.5	31	1 Sep	29.5	15 Aug	16.2	10 Feb	13.3	0.27
2.0	30	5 Oct	28.0	25 Sep	18.2	25 Feb	9.8	0.60
2.5	28	5 Oct	26.8	20 Oct	18.8	20 Mar	8.0	
							Average	0.33

[z] $D_T = (w/2)\ \{(Z_2 - Z_1)/\ell n(A_1/A_2)\}^2$, where $Z_2 - Z_1$ is the difference in depth, A_1/A_2 is the ratio of the max-mins between the two depths, and w is the frequency (rad/s) = $2\pi/(3600 \times 24 \times 365)$.

Table 11. Vertical curtain heat exchanger performance data.

time	green-house air temp. T_a	ave. water temp. $\bar{T}_w$	differ-ential water temp. ΔT_w	curtain area A	water flow rate F	heat trans. coef. U
	(°C)	(°C)	(°C)	(m^2)	(kg/s)	($W/m^2 \cdot C$)
11 September 1979; circulation fan on, duct fan off						
1400	52.0	23.7	0.5*	22	3.15	10.6*
12 September 1979; circulation fan on, duct fan off						
1250	47.0	24	0.31	22	2.7	6.9
22 September 1979; circulation fan off, duct fan on +						
1000	28.5	20.8	1.10	110	3.17	17.2
1100	31.4	21.7	1.44	"	"	17.9
1200	33.6	22.4	1.64	"	"	17.7
1300	34.8	23.2	1.64	"	"	17.1
1400	35.5	23.6	1.85	"	"	18.8
1500	35.3	23.7	1.82	"	"	18.9
1600	33.9	23.5	1.54	"	"	17.9
1700	31.0	22.4	1.08	"	"	15.2
					Average	17.6

* Temperature difference determined from single absolute thermocouples rather than differential thermopile.

\+ The average airspeed was about 1.0 m/s between the curtains as measured with a Thermo-Systems Model 1610 hot wire anemometer.

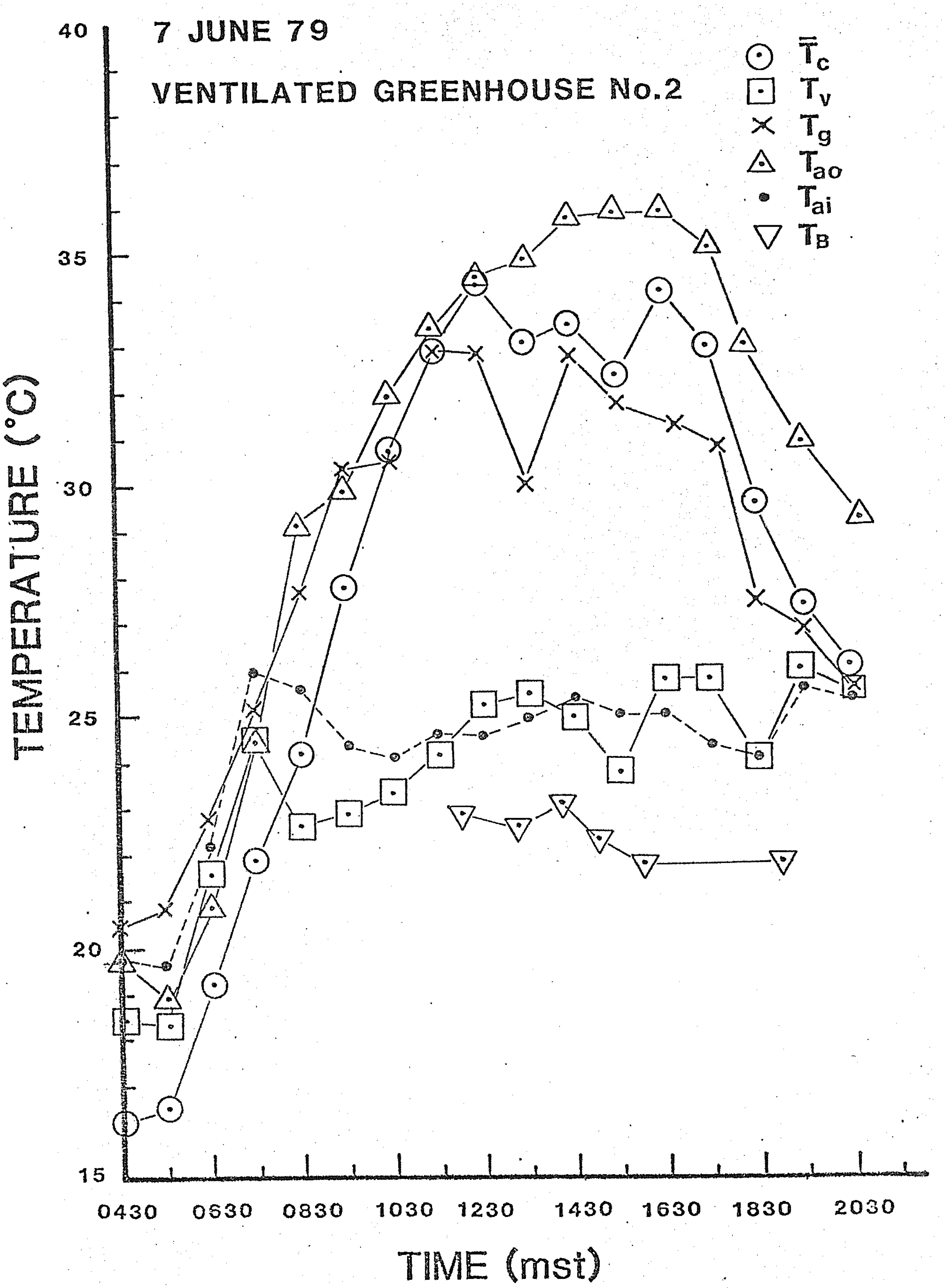


Figure 1. Average cover temperature, $\bar{T}_c$; vegetation temperature, T_v; soil surface temperature, T_g; outside air temperature, T_{ao}; inside air temperature, T_{ai}; and blotter leaf temperature, T_B; in ventilated greenhouse 2 on June 7, 1979.

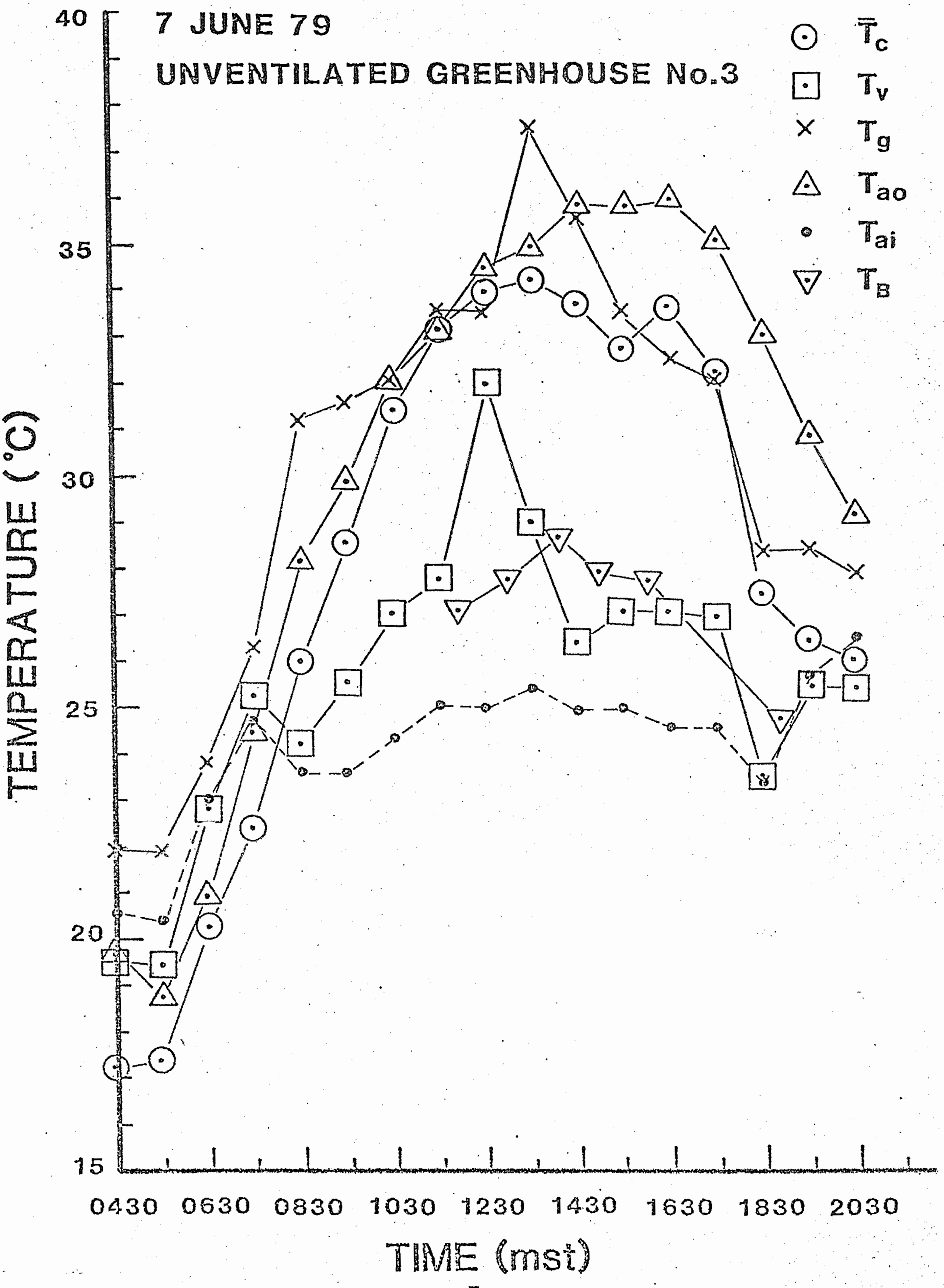
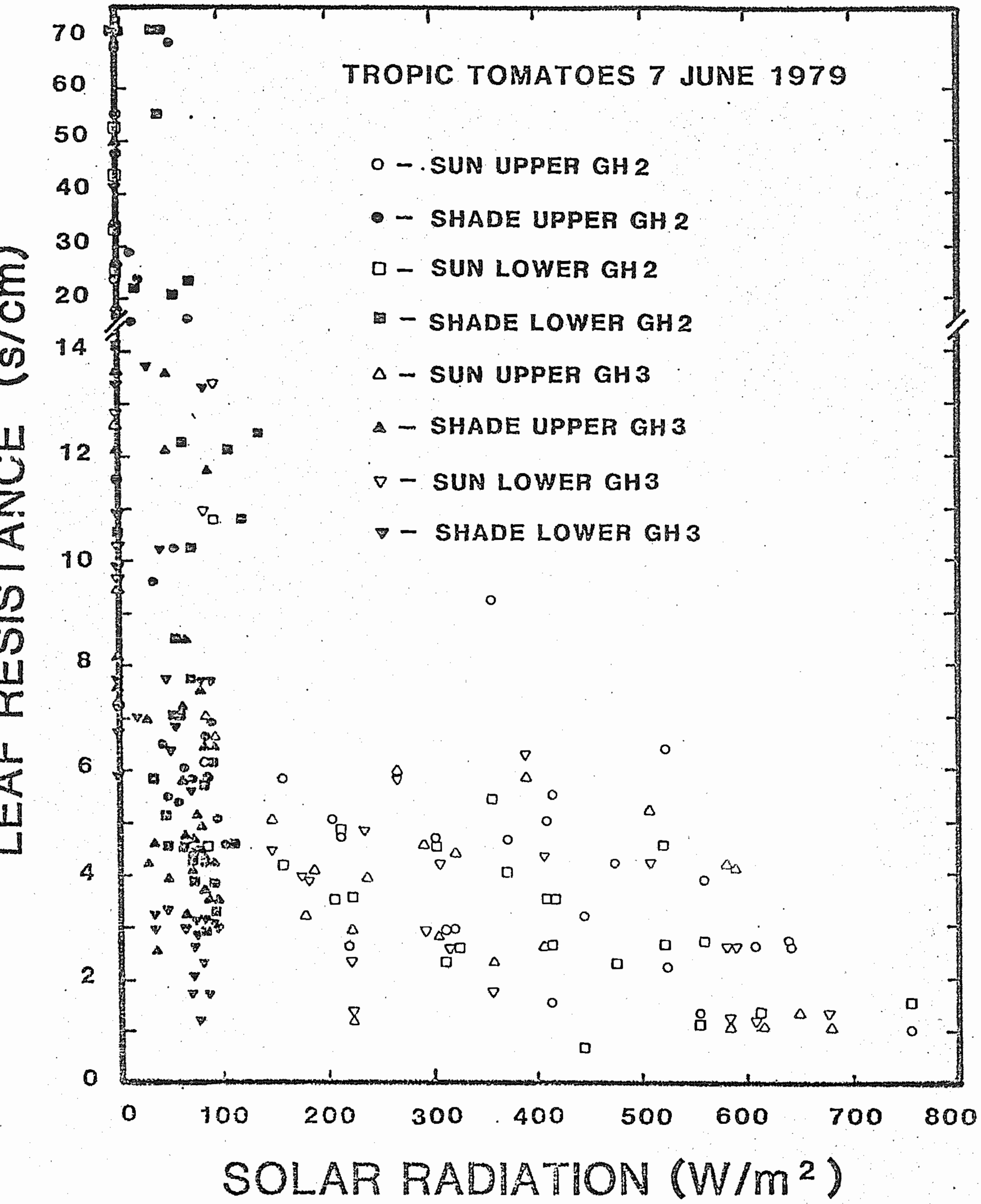


Figure 2. Average cover temperature, $\bar{T}_c$; vegetation temperature, T_v; soil surface temperature, T_g; outside air temperature, T_{ao}; and inside air temperature, T_{ai} in unventilated greenhouse 3 on 7 June 1979.



igure 3. Leaf resistance of 'Tropic' tomatoes vs solar radiation intensity. The data are for leaves in sunshine and in shade for the upper and lower leaf surfaces in ambient CO_2, ventilated greenhouse 2 and in 1000 μℓ CO_2/ℓ, unventilated greenhouse 3.

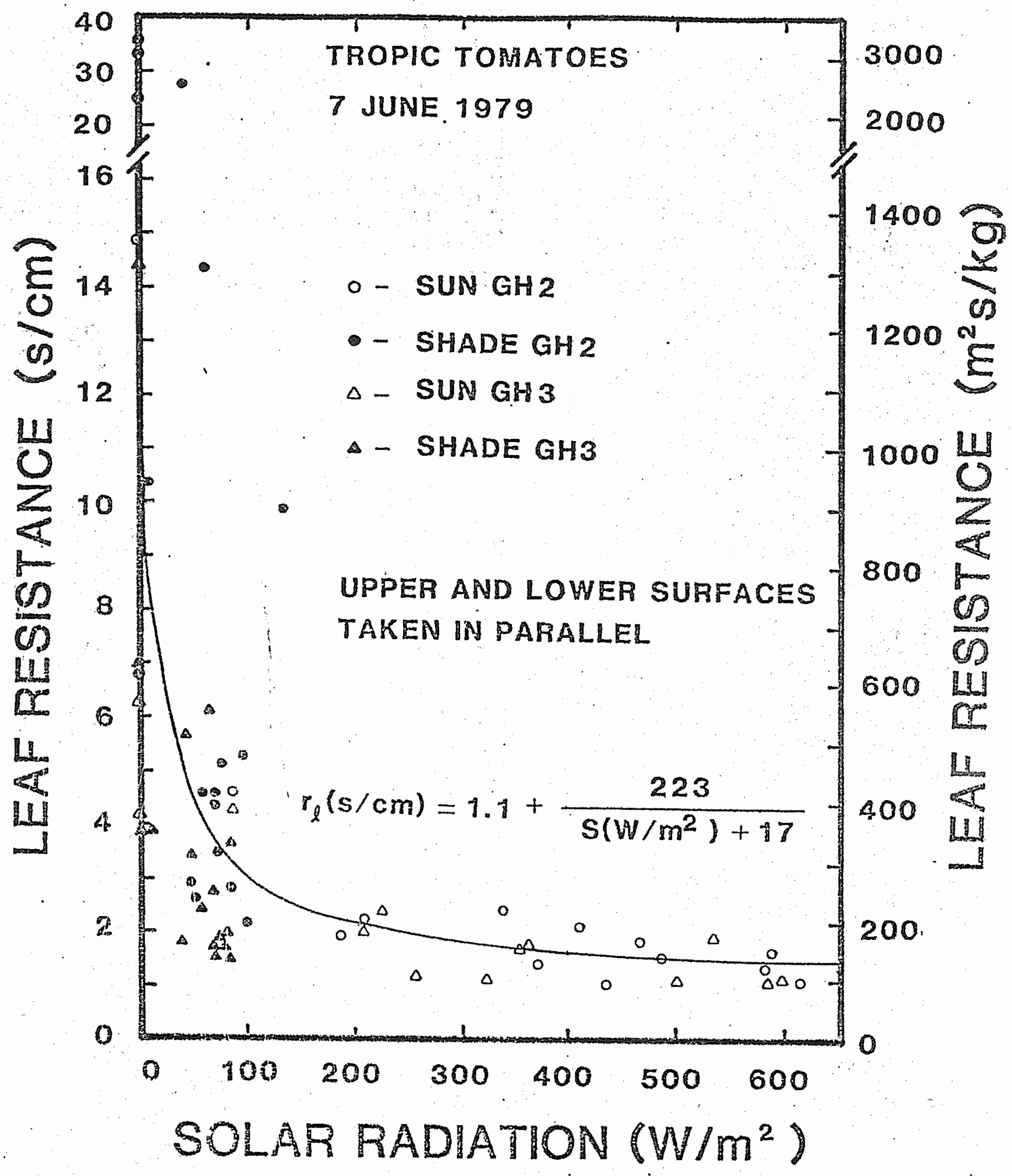


Figure 4. Leaf resistance of 'Tropic' tomatoes vs solar radiation intensity. The data are from sunlit and shaded leaves in the ambient CO_2, ventilated greenhouse 2 and the 1000 $\mu\ell$ CO_2/ℓ, unventilated greenhouse 3. Each data point was obtained by combining the upper and lower leaf resistance in parallel and then averaging the values from duplicate leaves that were measured at the same time.

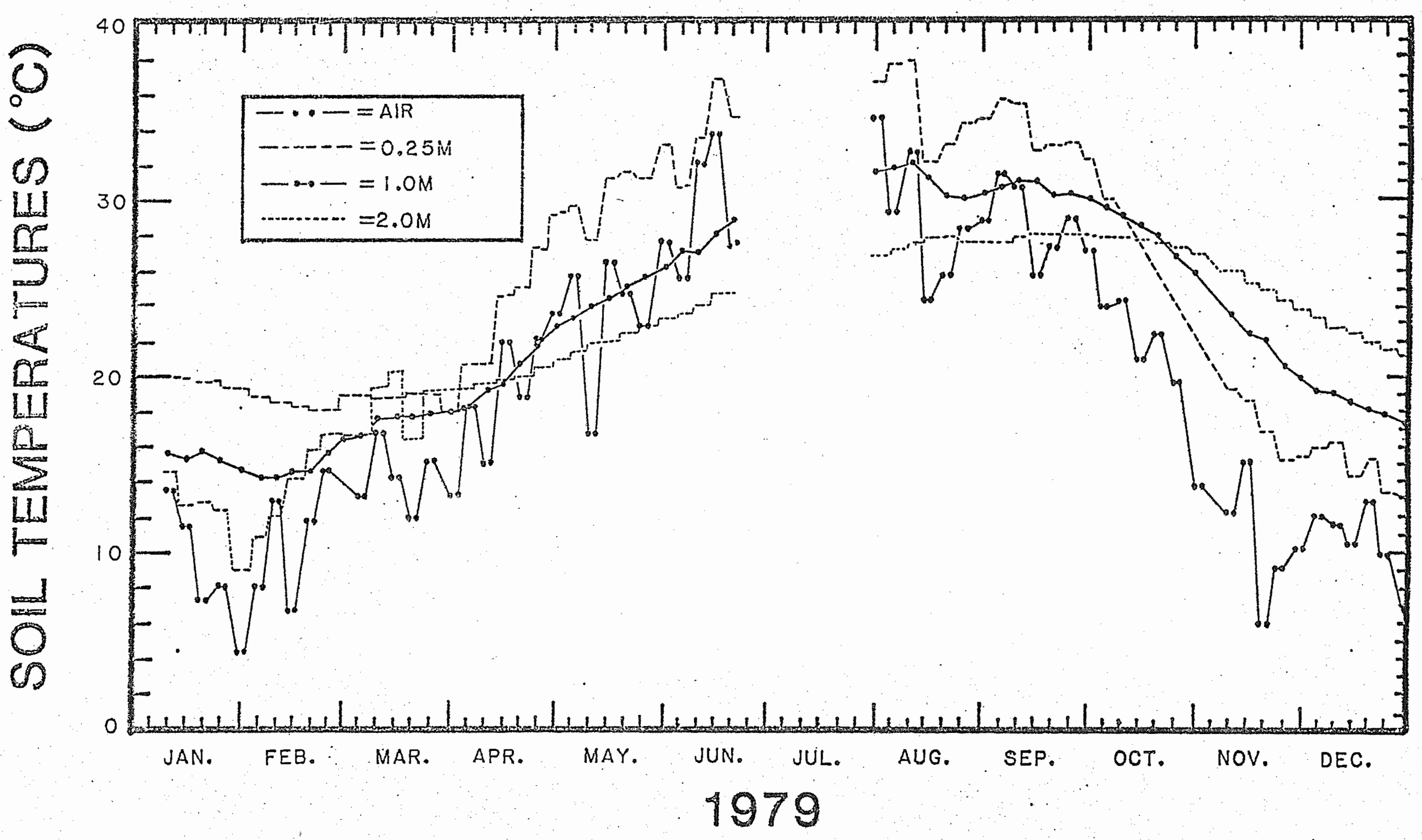


Figure 5. Soil temperatures at midnight and average daily air temperatures for bare Avondale loam in Phoenix, Arizona for 1979.

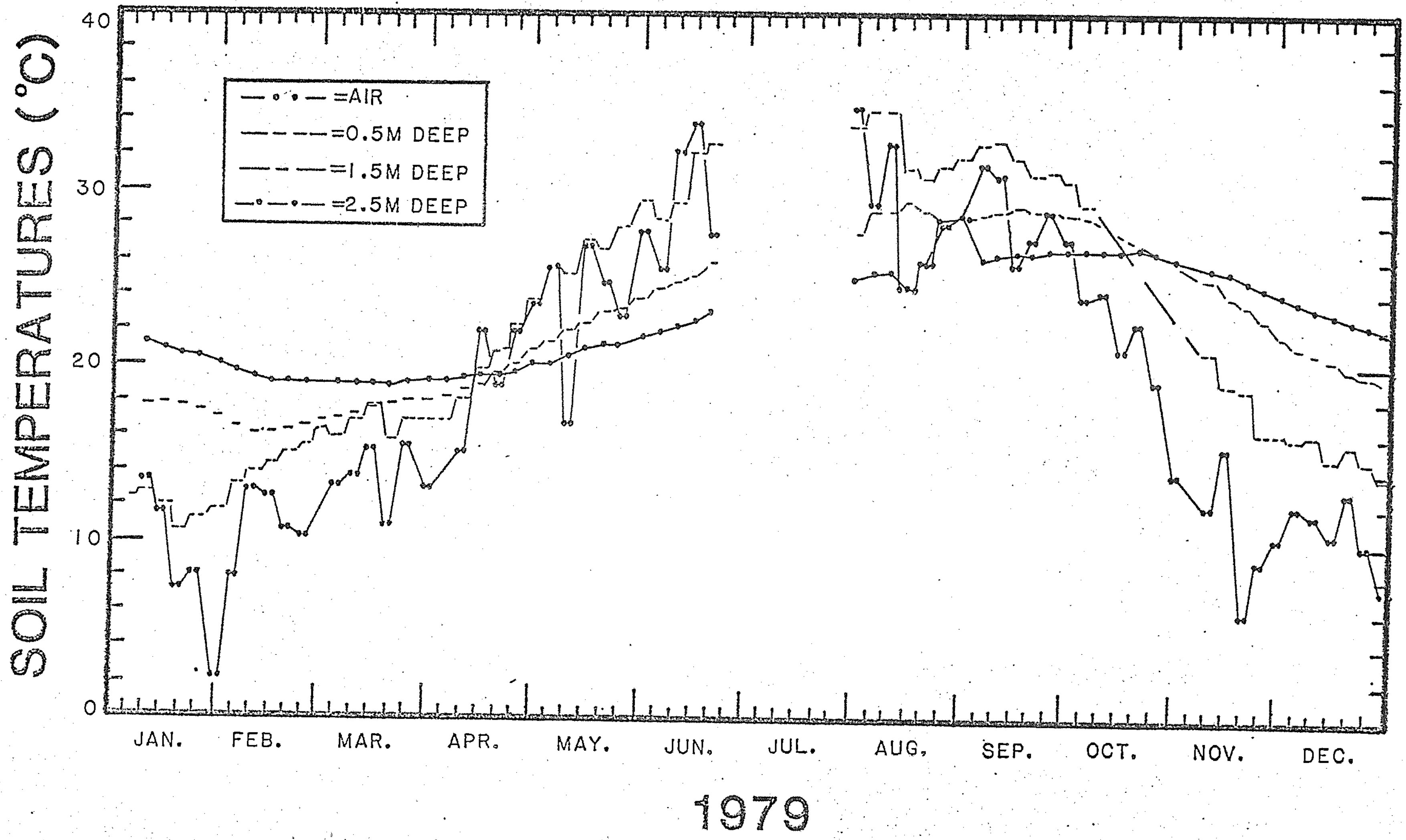


Figure 6. Soil temperatures at midnight and average daily air temperatures for bare Avondale loam in Phoenix, Arizona, for 1979.

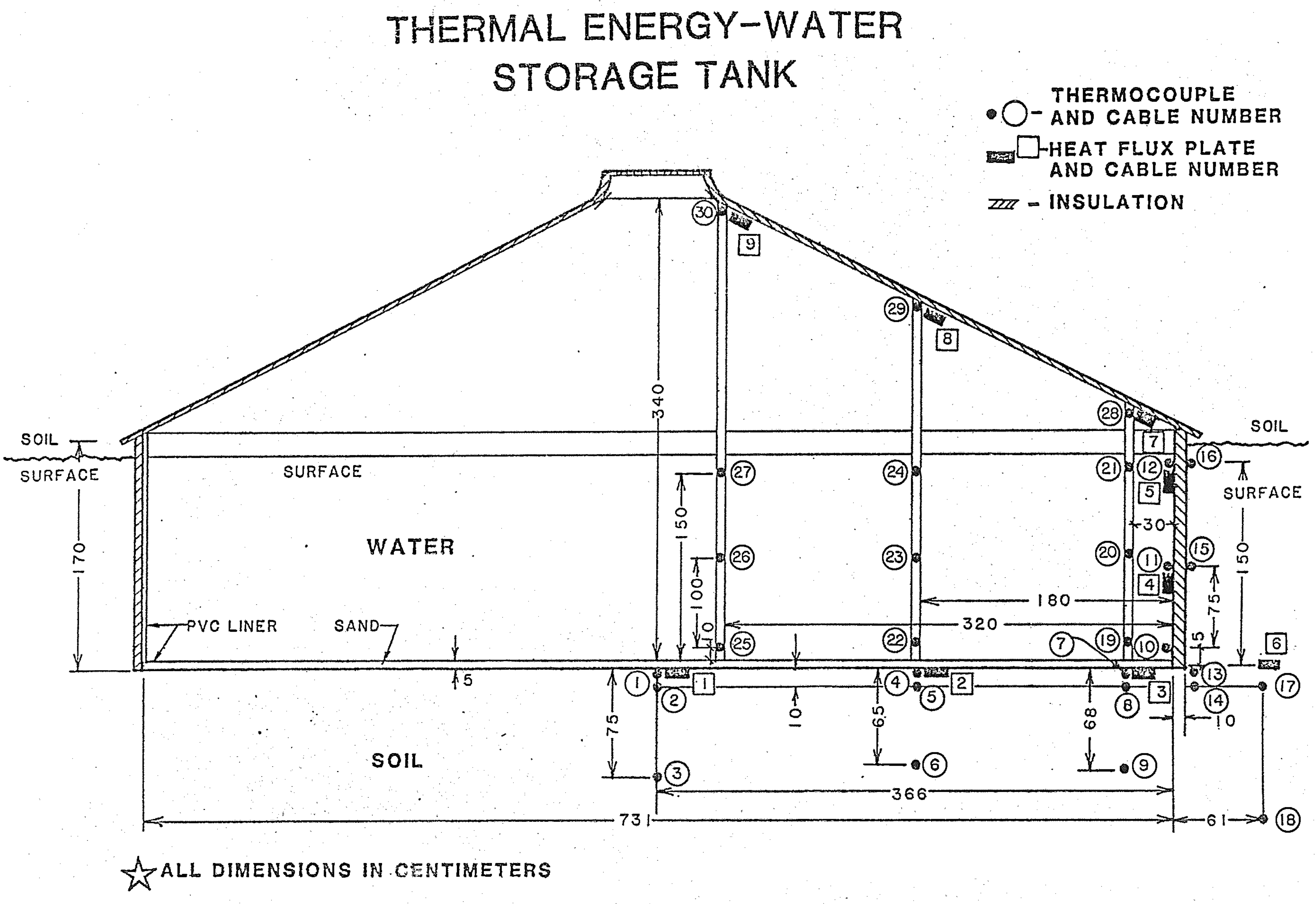


Figure 7. Cross-section of thermal energy-water storage tank showing dimensions and also placement of temperature and heat flux sensors.

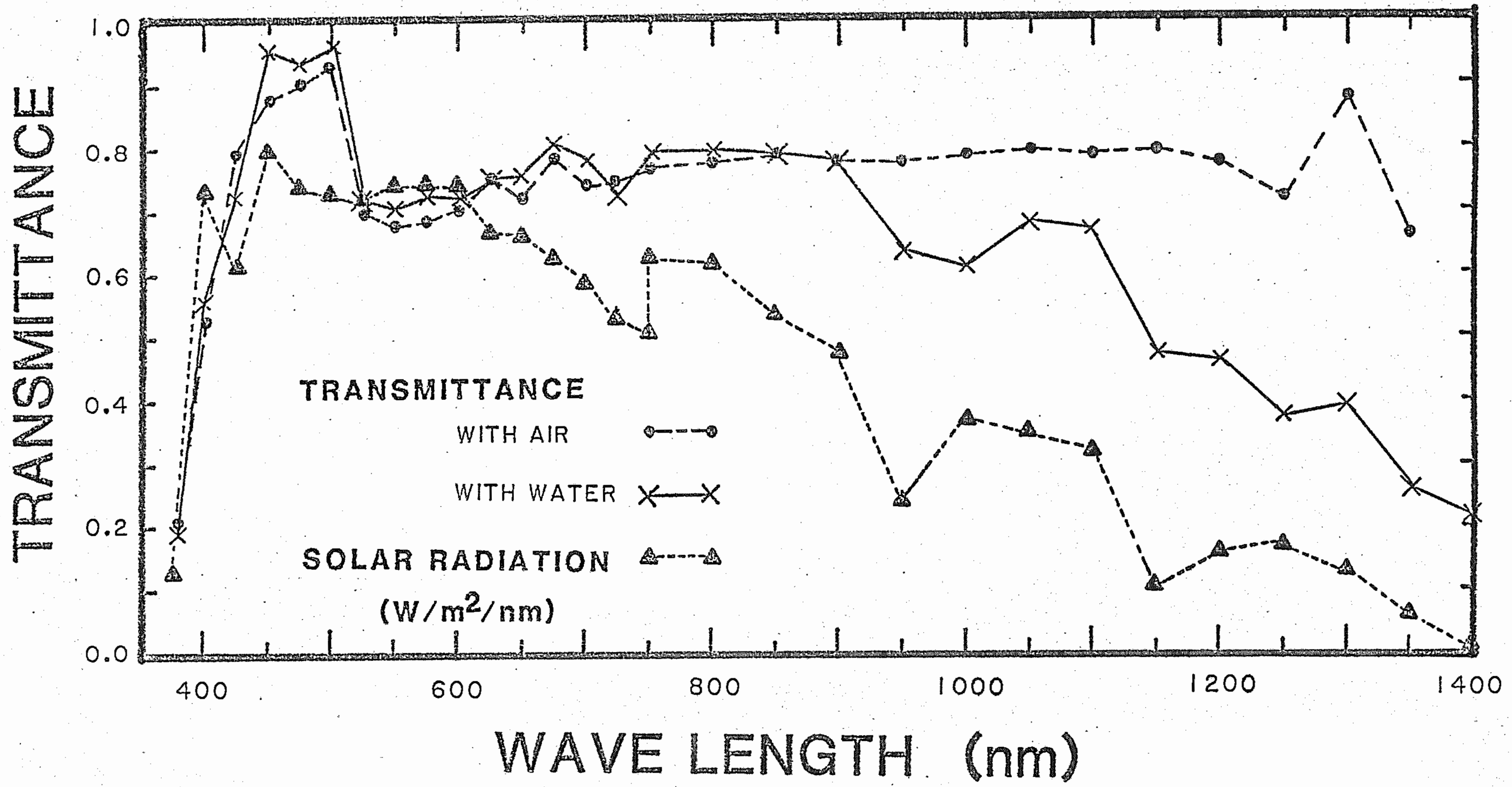


Figure 8. Transmittance of ¼-inch twin wall polycarbonate filled with air and with water vs wavelength. Also a solar radiation spectrum taken at about 1300 on 12 October 1979.

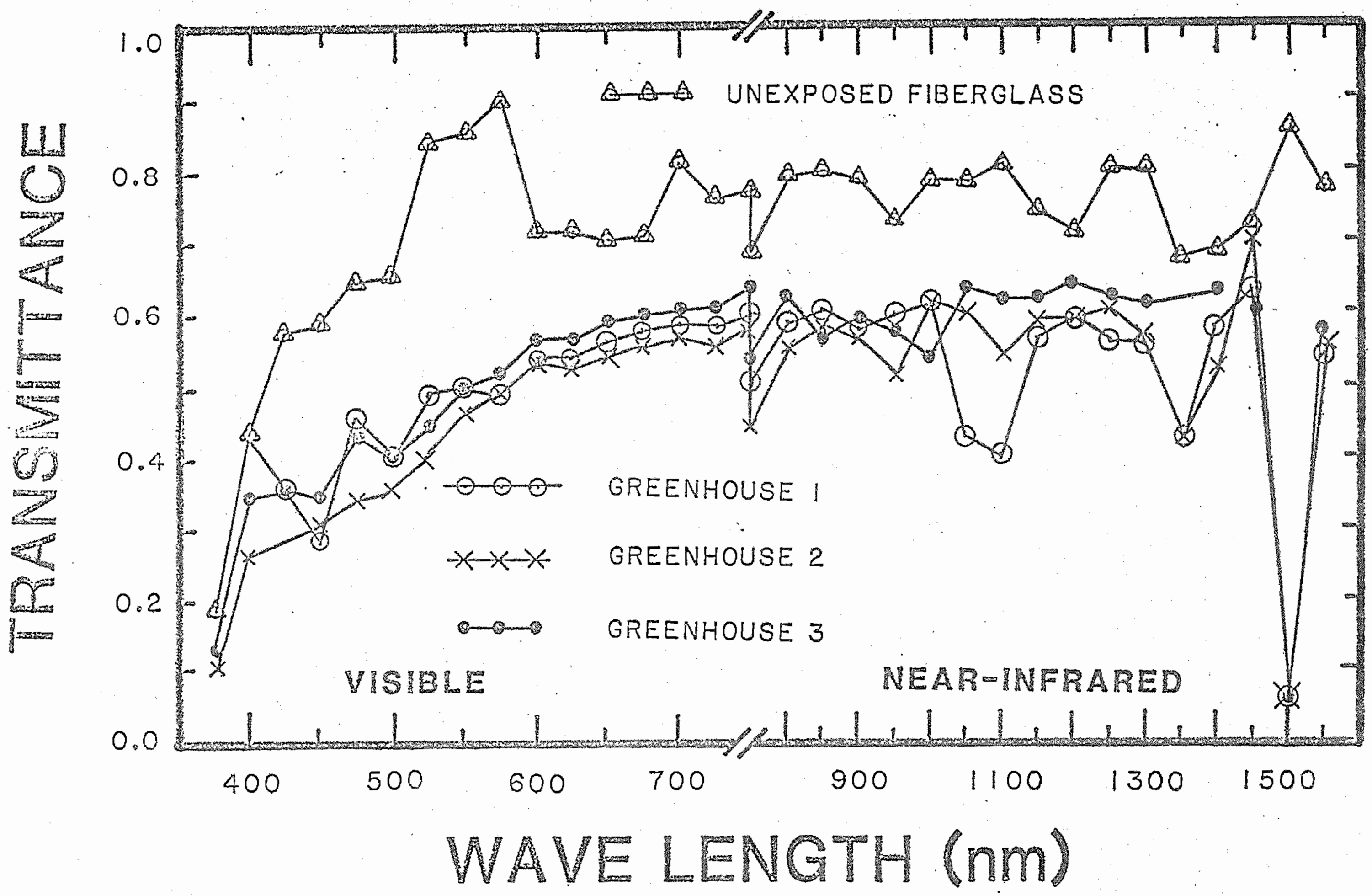


Figure 9. Transmittance of the roof of greenhouse 1 after 5 years; of greenhouse 2 and 3 after 3 years; and of an unexposed sheet of fiberglass.

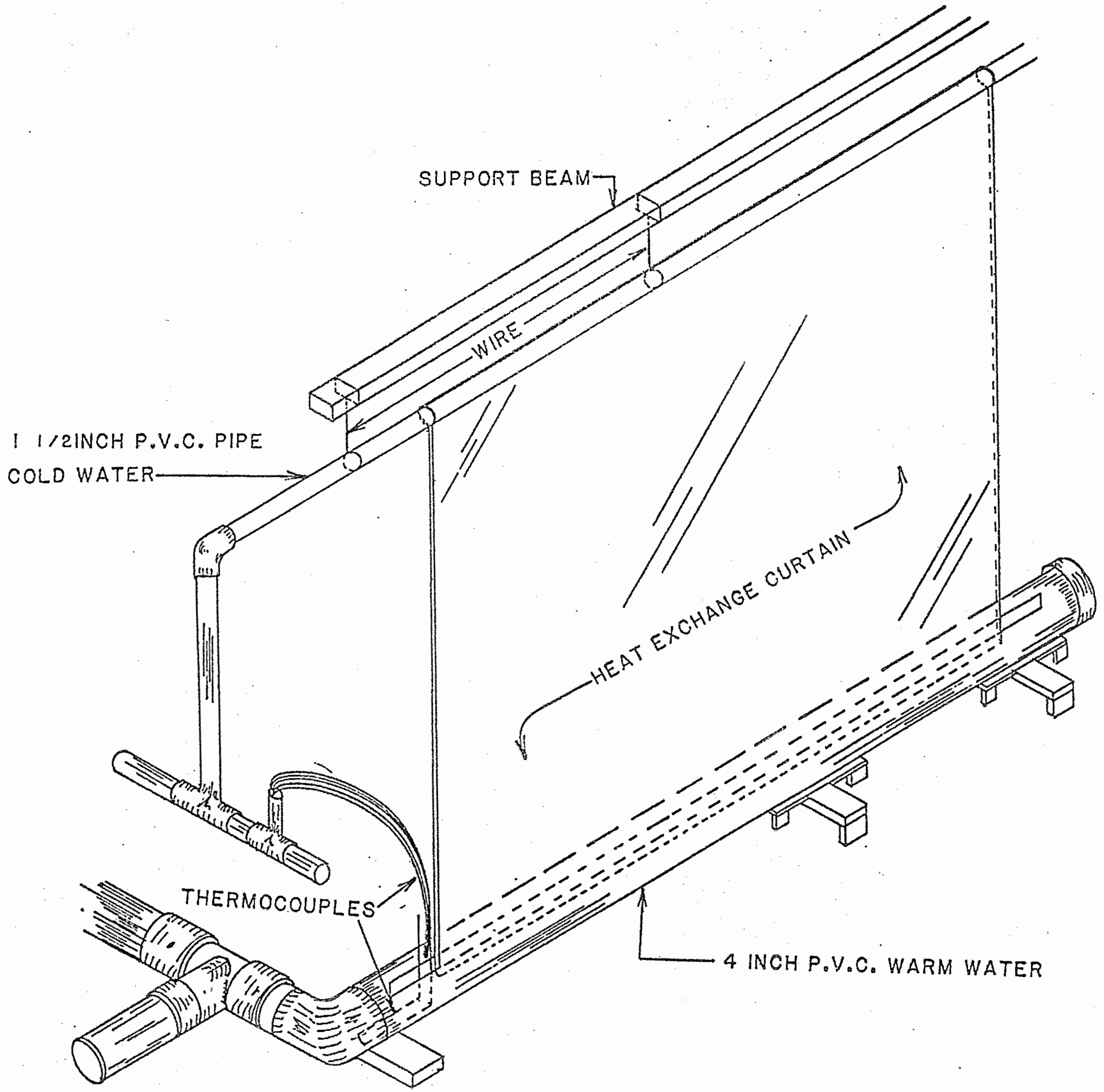


Figure 10. Schematic diagram of curtain heat exchanger.

TITLE: MICROBIOLOGY OF SOIL AND WATER SYSTEMS FOR RENOVATION AND CONSERVATION OF WATER

NRP: 20790 CRIS WORK UNIT: 5510-20790-002

INTRODUCTION:

During 1979, field and laboratory experiments were conducted to determine the rate of denitrification and nitrification in soils intermittently flooded with primary or secondary sewage effluent. This report summarizes results obtained on denitrification in soil basins from two land-treatment systems, the Mesa and 23rd Avenue Projects, and on nitrification from these projects and laboratory soil column experiments.

PROCEDURES:

Nitrogen transformations and nitrification-denitrification reactions responsible for N-removal were investigated on two field projects. The Mesa Project consisted of four small recharge soil basins (3 x 10 m) that were intermittently flooded with primary sewage effluent and dried, respectively, for seven days each. As a standard operational procedure, the Mesa Sewage Treatment Plant treated the primary effluent with ferric chloride for chemical removal of H_2S and odor control. The 23rd Avenue Project consisted of four large recharge soil basins (500 x 100 m) of about 10 acres that were intermittently flooded with secondary sewage effluent and dried, respectively, for nine days each. The water depth in the basins during flooding in both projects was about 20 cm. Soil samples were collected from each project only during the dry periods. Subsamples were extracted and analyzed, as soon as possible, for inorganic nitrogen components with an Automatic Technicon Analyzer. Other subsamples were prepared for measuring the rates of denitrification and moisture contents.

The acetylene inhibition method was used to quantitatively measure denitrification rates. The method blocks biological reduction of nitrous oxide to molecular nitrogen. Soil subsamples were placed in 40-ml septum vials and treated with about 90 µg NO_3-N/g, since nitrification was inhibited by acetylene (0.1 atm). Head space samples of 1.0 ml were obtained after incubation at 28 C for 24 hours and were analyzed for nitrous oxide with a gas chromatograph equipped with a thermal conductivity detector. Control soil samples without nitrate-N additions were also analyzed. The atmosphere in the vials was either helium or air with about 0.1 atm of acetylene.

Laboratory soil columns were used to determine the influence of ferric-chloride-treated primary sewage effluent on nitrification. 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.

RESULTS AND DISCUSSION

Nitrogen transformations and denitrification rates were determined in soils from wastewater recharge basins intermittently flooded with primary or secondary sewage effluent (Table 1). Denitrification rates were greatest during the first two to three days of drying. Soils flooded with primary effluent had denitrification rates that were considerably higher than soils flooded with secondary effluent, especially during the first two to three days of drying. Soils treated with helium plus nitrate-N had the greatest rates of denitrification, followed by soils treated with air plus nitrate and air only, respectively. The additions of nitrate-N increased denitrification for only two to three days in soils treated with air. Except for the first day of drying, the denitrification rates in the air-only treatments are the most accurate estimates of denitrification rates during drying in the surface soil (0-5 cm) of an undisturbed soil basin. On the first day of drying, the low rates of denitrification in soil treated with air only resulted from the low amount of nitrified-N in the soil sample and the inhibition of nitrification by acetylene. With nitrification inhibited, denitrification could not occur, so nitrate-N was added to soils treated with air and helium. The amount of nitrate-N added during the first two to three days of drying produced denitrification rates that were greater than they would have been in the natural soil basin. These results have indicated that environmental conditions necessary for denitrification are present in the surface of the soil basins for only 48 to 72 hours at the start of the dry period and that the most important factors limiting denitrification were the rates of nitrification and concentration of nitrite-N and/or nitrate-N.

The nitrogen transformations in soil basins flooded with secondary effluent showed a natural and expected conversion of ammonium-N to nitrified-N (Table 1). However, the nitrification processes in soil basins flooded with primary effluent were apparently inhibited during the first two to three days of drying and after three days of drying showed essentially no loss of ammonium-N or accumulation of nitrified-N. Besides the higher BOD's of the primary effluent and wet surface soil that would utilize and restrict oxygen supplies necessary for nitrification, the addition of ferric chloride for chemical removal of hydrogen sulfide and odor control may have been a major factor contributing to the inhibition of nitrification. Soil column experiments further confirmed the inhibitory effect of the Mesa primary effluent on nitrification (Table 2). Nitrification appeared to be completely inhibited during eight days of incubation in soil treated with the primary effluent from the Mesa Treatment Plant; whereas nitrified-N had accumulated in soil samples treated with other water sources, which included primary and secondary effluents from the 23rd Avenue Treatment Plant and irrigation water from a Salt River Project canal that was treated with ammonium. These results indicated that sewage effluents treated with chemicals that inhibited nitrification should not be used on land-treatment systems designed and managed for maximum N-removal by denitrification.

SUMMARY AND CONCLUSIONS:

Microbiological studies to characterize the growth and activity of denitrifying bacteria in soil basins intermittently flooded with secondary sewage effluent and to develop techniques and procedures for quantitatively evaluating the denitrification process in the soil basin were conducted.

The acetylene inhibition method that blocks nitrous oxide reduction to nitrogen gas quantitatively measured the denitrifying activity of field samples from soil basins intermittently flooded with either primary or secondary sewage effluent. The results indicated that maximum denitrifying activity occurred only during the first 48 to 72 hours of the dry period. These denitrification rates were about 41 and 11 µg N_2O-N/g/day, respectively, for surface soil (0-5 cm) previously flooded with primary or secondary effluent. After 72 hours the activity decreased to values of <10 and <5 µg N_2O-N/g/day, respectively. The addition of nitrate-N to field soil samples markedly increased denitrification during the first 48 to 72 hours of the dry period and after 72 hours nitrate-N additions did not enhance denitrifying activity. This further indicated that environmental conditions for maximum denitrification are present in the surface soil for only the first 48 to 72 hours of the dry period. Since the first requirement for denitrification was the conversion of the ammonium-N to nitrite- or nitrate-N, then nitrifying activity during the first 48 to 72 hours controlled the magnitude of denitrification. If nitrification were inhibited by unfavorable environmental conditions or chemical inhibitors during the first 48 to 72 hours, then the potential N-removal by denitrification would be reduced. The results obtained with primary effluent have indicated that the higher BOD's and the wet surface soil conditions after flooding are utilizing and restricting the oxygen supply needed for higher nitrifying activity. Also, the primary effluent was treated with iron chloride for odor control, which may have caused a further reduction in nitrifying activity, that persisted throughout the dry period. In conclusion, the major factor limiting denitrification was the concentration of nitrite- or nitrate-N produced by nitrification during the first 48 to 72 hours of the dry period. The carbon energy needed for denitrification was also an important limiting factor with secondary effluent, but not with primary effluent.

PUBLICATIONS

1. Bouwer, H., Rice, R. C., Lance, J. C., and Gilbert, R. G. Ten years of rapid-infiltration search--the Flushing Meadows Project, Phoenix, Arizona. Jour. Water Poll. Control Fed. (Sub for Pub).

2. Bouwer, Herman, Rice, R. C., Lance, J. C., and Gilbert, R. G. Renovation of sewage effluent with rapid-infiltration land-treatment systems. Jour. Amer. Water Works Assoc. (App. for Pub.)

3. Gilbert, R. G., Lance, J. C., and Miller, J. B. Denitrifying bacteria populations and nitrogen removal in soil columns intermittently flooded with secondary sewage effluent. Jour. of Envir. Quality 8(1):101-104 Jan-Mar 1979.

4. Gilbert, R. G. Nitrous oxide and other gases in soil basins intermittently flooded with secondary sewage effluent. 71st Annual Meeting, Amer. Soc. Agron. and Soil Sci. Soc. Amer., Fort Collins, Colorado. 5-10 August 1979. Agron. Abstr. p. 157.

5. Lance, J. C., Rice, R. C., and Gilbert, R. G. Renovation of sewage water by soil columns flooded with primary effluent. Jour. of Water Pollution Control Fed. (In press).

6. Love, T. D., Sommerfeld, M. R., and Gilbert, R. G. Algal bioassay of waste and natural waters of the Phoenix, Arizona area. Jour. of Water Research. (In press).

PERSONNEL: R. G. Gilbert, J. B. Miller, and K. C. Adamson.

Table 1. Nitrogen transformations and denitrification rates in soil basins intermittently flooded with primary or secondary sewage effluent.

Effluent Type	Days Dry	Soil Nitrogen 1/ Ammonium-N		Nitrified-N	Denitrification Rates 2/ He + NO_3-N	Air + NO_3-N	Air (only)	Water Content
		(μgN/g)			(μgN_2O-N evolved/g/day)			(%)
	1	305	(306)	1	57	66	<1	26.2
	2	232	(270)	38	103	94	24	14.5
Primary	3	195	(336)	141	142	79	41	14.4
	4	213	(347)	134	89	16	20	8.8
	7	199	(367)	168	57	13	<10	7.2
	1	110	(111)	1	63	19	<1	24.0
	2	91	(127)	28	58	23	11	21.9
Secondary	3	64	(121)	57	78	9	8	15.6
	4	41	(121)	80	75	10	5	16.8
	7	33	(155)	122	74	8	<5	11.8

1/ Soil samples were collected, extracted and analyzed as soon as possible for NH_4-N, NO_2-N and NO_3-N. Nitrified -N was the μgNO_2&NO_3-N/g. The parentheses indicate the total inorganic nitrogen.

2/ Denitrification rates were measured in soil samples collected during dry periods with the acetylene inhibition method. Soil samples were incubated for 24 hours in flasks containing helium or air and 0.1 atm. of acetylene. Nitrate N additions were equivalent to 91 μgNO_3-N/g of soil.

Table 2. Nitrification in soil columns treated with primary and secondary effluents. 1/

Soil Treatments 2/	Incubation Time (Days)	Ammonium-N (μgNH_4-N/g)	Nitrified-N (μgNO_2^- + NO_3-N/g)
Primary Effluent:	0	139	0
Mesa Project	1	138	0
	4	149	1
	8	154	0
Primary Effluent:	0	95	0
23rd Ave. Project	1	95	0
	4	81	3
	8	22	36
Secondary Effluent:	0	82	0
23rd Ave. Project	1	72	5
	4	12	50
	8	7	89
Irrigation Water:	0	91	0
Salt River Project	1	72	9
	4	43	19
	8	18	45

1/ Soil from basin #3, 23rd Ave. Project, was packed into soil columns of 5-cm depth and flooded with a hydraulic head of 50 cm for about 24 to 36 hours or until 20 ℓ of water had infiltrated through the soil.

2/ Primary effluent from the Mesa Project was routinely treated with Ferric chloride for removal of H_2S and odor control. The irrigation water was amended with NH_4Cl to give 25 mg NH_4-N/ℓ.

TITLE: WASTEWATER RENOVATION BY SPREADING TREATED SEWAGE FOR GROUNDWATER RECHARGE

NRP: 20790 CRIS WORK UNIT: 5510-20790-003

INTRODUCTION:

The flood-damaged Flushing Meadows site was inspected in the spring of 1979. Damage was quite severe and since the 10-year project has produced a rather well-rounded study, reactivating the Flushing Meadows project is not planned.

Construction of the bypass channel at the 23rd Ave. Rapid Infiltration Project (see Fig. 22 in 1977 Annual Report) was completed in late spring of 1979. This channel bypasses the 80-acre pond, so that secondary effluent from the treatment plant can enter the basins directly without having to flow first through the 80-acre oxidation pond. Algae growth in this pond drastically increased the suspended solids content of the effluent in the summer and was the principal reason for the low hydraulic loading rates in the infiltration basins due to soil clogging (see Annual Reports 1978 and 1979). Regular flooding of the four infiltration basins, which was halted in September 1976 because of low infiltration rates and the need for constructing the bypass channel, was resumed on 26 June 1979.

The main objectives of the 23rd Ave. Project are to evaluate hydraulic loading rates with the new quality secondary effluent, quality of renovated water (including trace organics), response of groundwater level to infiltration, evaluation of aquifer properties, analysis of underground flow system, and protection of adjacent native groundwater against encroachment by renovated sewage water. Several meetings were held with the City of Phoenix, Roosevelt Irrigation District, EPA, Arizona Department of Health Services, and consulting engineers' firms to develop plans for the use of the renovated water for unrestricted irrigation by the Roosevelt Irrigation District. These plans include drilling of additional wells on the center dike of the 40-acre system, and expansion of the system to 120 acres by also converting the 80-acre pond into infiltration basins. The dikes in this pond would run north-south and the basins would be filled from the new bypass channel. The wells for pumping renovated water would be located midway on the dikes, thus extending the line of wells on the center dike of the 40-acre system.

The studies on rapid infiltration of primary effluent at the Mesa Sewage Treatment Plant were concluded in July 1979. Column studies were initiated in the spring of 1979 to determine if sludge amendments to sands could increase the cation exchange capacity of the sand to obtain sufficient adsorption of ammonium during flooding for subsequent nitrification and denitrification during drying. Dune sands, flood plains, and other sandy soils are often available for rapid-infiltration of sewage effluent but their natural cation exchange capacity is too low for effective nitrogen removal. Sludge amendments also may reduce infiltration rates, which in turn should increase the removal of nitrogen and other substances from the sewage effluent as it percolates down through the sand to become renovated water.

The flooding of the Salt River bed in 1978 and 1979 has renewed the interest in groundwater recharge. This includes both the natural infiltration and groundwater recharge when the river is flowing, and artificial recharge from specially constructed infiltration basins. Because infiltration rates are so much dependent on the sediment concentration of the water in the river, a laboratory study was carried out to obtain a better idea of what infiltration rates can be expected for floodwater with varying sediment concentrations.

I. TWENTY-THIRD AVENUE PROJECT

Modifications and additions to the 23rd Ave. Project other than the bypass channel include an attachment of a rectangular weir to the bottom of the slide gates in the outlet structures. These weirs make it possible to maintain relatively constant depth in the basins while recording the outflow rate. The North well was equipped with a domestic-type submersible pump (10-20 gpm capacity) to obtain samples of renovated water. The pump was placed about 10 ft above the bottom of the hole bottom to collect as good a sample of "aquifer" water as possible. From 7 to 12 December, three new wells were installed in the center of the project, northeast of the center well (Fig. 1). The wells are cased with 6-in. steel pipe to the bottom and are 60, 80, and 100 ft deep, respectively. These wells make it possible to sample renovated water in the center of the project and from the upper portion of the aquifer. Samples will be obtained from the well with the least penetration into the aquifer. Since 1975, the water table depth has ranged between 40 and 90 ft. The wells were drilled with the air-rotary method to avoid local contamination of the aquifer with drilling mud or other additives. The renovated water samples thus should be suitable for trace-organics analyses. A domestic-type submersible pump has also been installed in the 60-ft well with the intake a few feet above the bottom. The cuttings evacuated from the three wells during drilling indicated that the materials in the vadose zone and the aquifer consisted mostly of sand and gravel. Very few fines were encountered. The three new wells are located on an east-west line that is 20-ft north of the center well. Direct distances from the center well are 73.5 ft for the 100-ft well, 83.0 ft for the 80-ft well, and 93.8 ft for the 60-ft well. The air-rotary rig was also used to clean and develop the bottom of the existing south well. This well was drilled with the cable-tool method in 1975. It never responded very well to water table changes, probably because it was clogged at the bottom or it ended in material of low permeability. After redevelopment with the rotary rig, the well response was much better. Elevations of the tops of the various well casings and of two outflow boxes are shown in Table 1.

I.1. Basin Management, Infiltration Rates, and Algae.

Because of above-average rainfall in the winters of 1977 and 1978, considerable vegetation had grown in the basins during the period of inactivity that started in September 1976. Most of the vegetation consisted of annuals, which dried in the spring and summer. However, there was also considerable growth of salt cedars, particularly in Basin 4. Salt cedar also developed in the east side of Basin 3, and in a more scattered fashion in Basin 1. Basin 2 had the fewest salt cedars. Many of the salt cedars were over 8 ft tall at the end of 1979. While scattered growth of salt cedar is not objectionable, dense stands should be avoided because they shade the bottom and retard the drying and infiltration recovery process. Thus, most of the salt cedars will have to be removed before they get too large. The normal schedule of flooding and drying generally prevents development of vegetation. Established vegetation, particularly salt cedars and other plants that grow above the water, however, thrives under the intermittent application of sewage effluent. The bottom condition of the basins when flooding was resumed in June 1979, thus was mostly bare soil with considerable dead vegetation and scattered salt cedars about 8 ft tall.

The outflow weirs at the west end of the infiltration basins (Fig. 1) were set to maintain an average water depth of about 0.8 ft in the basins. This was considerably less than the 3 ft maintained in the 1975-76 period. A smaller water depth was considered preferable, however, to reduce the surface detention time of the effluent water in the basins and, hence, reduce the growth of algae. For example, if the infiltration rate is 1 ft/day and the water depth is 1 ft, the average turnover time of the effluent in the basin is one day. However, if the water depth is 3 ft, the turnover time would be three days, assuming that the infiltration rate remains the same. This assumption is reasonably valid, since water depth has a minor effect on infiltration rate after the wet front has advanced a sufficient distance and if there is no surface clogging of the soil.

Flooding and drying periods were nine days each. Deviations of one or two days sometimes occurred due to weekends or to accommodate a study on nitrogen transformations in the soil (see Annual Report section by R. G. Gilbert). Infiltration rates for the first inundation period were so high (about 6 ft/day) that only one basin could be flooded at a time. Thereafter, the basins were flooded in pairs, symmetrical with respect to the center dike (see flooding and drying schedules in Fig. 7). At the end of October, the secondary effluent contained more fine suspended solids and assumed a greyish color. This caused more clogging of the soil in the infiltration basins, and longer drying periods were required for all the effluent to disappear into the ground. Thus, starting in November, only one basin was flooded at a time and the sequence for each basin was one week flooding-three weeks drying. Infiltration rates for the basins, calculated from the difference between the inflow and outflow rates, are shown in Figs. 2, 3, 4, and 5. The infiltration rates still showed considerable decrease during flooding, indicating that soil clogging still took place. However, since the algae content of the secondary effluent was much less than before construction of the bypass channel, the basins dried rapidly and there was good infiltration recovery.

Accumulated infiltration rates are shown in Fig. 6. All curves exhibit about the same slope, indicating that the basins all have about the same infiltration characteristics. The reason that the curves for basins 1 and 4 are below those for basins 2 and 3 is that basins 1 and 4 got a later start. The hydraulic loading rate for a full half year of operation thus appears to be about 125 ft, which amounts to about 250 ft/year. This figure probably could be increased by using a larger depth in the basins, by periodic removal of the solids that accumulate on the bottom of the basins and breaking up the surface crust, and by reducing the suspended solids content of the secondary effluent during the winter months. One way to reduce the suspended solids content of the effluent is to pass the secondary effluent through the 80-acre pond before it enters the bypass channel. This could be done by closing the inlet gate on the east end of the bypass channel (see Fig. 22 in 1977 Annual Report), opening the inlet gate to the 80-acre pond on the east side, and opening gate A (Fig. 1) on the end of the bypass channel. However, effluent leaked around gate A and a temporary dam (B in Fig. 1) had to be placed near the end of the bypass channel to prevent the dike from washing away around gate A. Previous data indicated that algae growth in the 80-acre pond was minimal during the winter time. Thus, the beneficial effect of settling of suspended solids probably would outweigh the adverse effects of additional algae growth in the winter. The reverse, of course, is true in the summer. Increasing the water depth in the basins would be most appropriate in the winter, when there is little algal growth in the water, and longer surface exposure times will not be objectionable. Larger water depths may also produce better settlement of suspended solids in the upper end of the infiltration basins, thus reducing clogging of the soil surface in the rest of the basin. Where the infiltration is limited by clogging of the soil surface, infiltration rates can be expected to vary directly with water depth.

In view of the above considerations, a design hydraulic loading rate of 300 ft/year seems reasonable. This would give the 40-acre system a capacity of 12,000 acrefeet per year, or about 11 mgd or 7640 gpm. To pump renovated water out of the aquifer at this rate will require three wells, each pumping about 2550 gpm. The wells probably should be at least 300 to 400 ft deep and should be perforated from 100 ft down. A hydraulic loading rate of 300 ft per year would be about 14% of the average vertical hydraulic conductivity of the soil in the basins, assuming that the infiltration rate of approximately 6 ft/day obtained when the basins were first flooded and the effluent advanced as sheet flow over the soil is a reasonable reflection of the vertical hydraulic conductivity of the upper soil layers.

The projected design hydraulic loading rate of 300 ft per year is much higher than the rate of 71 ft per year obtained in the period 1975-1976. The difference, of course, is due to the greatly reduced suspended solids (algae) content of the effluent going into the infiltration basins following the completion of the bypass channel. The suspended solids content of the effluent entering the infiltration basins generally was below 10 mg/ℓ, and that of the effluent leaving the basins was often even lower (see Suspended Solids, page 15-10). This is much less than the suspended solids contents found before construction of the bypass channel, which were on the order of 10 to 20 mg/ℓ in the winter and 50 to 100 mg/ℓ in the summer for the effluent entering the infiltration basins. Algae still grew in the infiltration basins, but they were more of the kind that grow on the bottom or float on the surface than the unicellular, suspended algae that previously gave the water such a green appearance. Thus, the effluent water itself in the infiltration basins remained quite clear.

Samples of floating and bottom algae and of the clear effluent itself were taken in July and November for algae identification. This work was done by Mr. Andrew J. Lampkin III of the Department of Botany and Microbiology of Arizona State University. The main algae types in the bright green algae layer floating on the water were <u>Chlamydomonas</u> and <u>Pandorina</u>. These algae are vegetatively motile. The surface layer consisted mainly of non-motile resting stages (zygotes or aplanospores). <u>Oscillatoria</u> appeared to be the dominant mat-forming blue-green algae on the bottom of the basins. They were also noted in other samples (surface and plankton), as could be expected from the kinetics of mat formation and subsequent breakup. The main suspended or planktonic algae species was <u>Carteria klebsii</u>. This is the dominant bloom organism that probably caused the effluent to be so green and high in suspended solids when it went through the 80-acre pond before construction of the bypass channel. A complete list of the algae in the various samples is presented in Table 2.

I.2. Groundwater levels

Water level elevations in the north well (NW) and center well (CW) (Fig. 7) were at alltime highs due to extended periods of flow (several months) in the Salt River, which runs just south of the project, in the first part of the year. The water level in NW peaked in the beginning of April at a depth of about 33 ft below the top of the dike, or about 28 ft below the bottom of the basins. In previous years (1976 and 1978), the 75-ft deep NW had actually become dry. The general decline of the water level in NW in the period April-July was most likely caused by dissipation of the groundwater mound formed by recharge from the Salt River bed, and by pumping of groundwater north of the project. The water level in NW rose when infiltration was first started (in basin 3), even though basin 3 was not the closest basin to the well. When basin 3 was no longer flooded, the water level in NW dropped, and then rose when basin 2 was flooded. The water level dropped again when basin 2 was dried and then significantly rose in the beginning of July when basins 1, 2, and 3 were all flooded about the same time, etc. The general rise of the water level in NW starting about the middle of July is probably due to recharge from the infiltration basins and to a reduction in groundwater pumping from the wells north of the project later in the summer.

The water level in the north well also showed the typical response to the normal diurnal changes in barometric pressure. During the day, heating of the air causes barometric pressures to decrease which in turn causes the water level in the well to rise. At night, the reverse takes place. These effects are illustrated for the period 26-28 May in Fig. 8. Despite the fact that the water level was in a declining trend, slight water level rises occurred just after noon when the barometric pressure was lower.

The water level in CW was measured with a bubble tube, using a 100 psi-pressure gage for pressure measurement. Resulting water level elevations were considerably lower than those measured for the other wells in the project. This was originally attributed to the fact that the well was perforated from 100 to 180 ft and that, hence, the water level represented some "average" hydraulic head for that depth range. When this average head appeared unreasonably low, however, a hole was drilled through the pump base of the well to measure the water level directly with the electrical probe. This measurement, which was taken in January 1980, showed that the bubble tube underestimated the water level height in CW by 15 ft. Thus, all previous water level elevations obtained with the bubble tube were increased by 15 ft. The same correction should also be applied to the CW water levels reported in 1975 and 1976, when these water levels were below those for the NW. For the period February-April 1976, however, the measured water levels in CW were higher than those in NW, which is reasonable. Then, the CW data suddenly dropped below the NW data in April 1976, possibly because of a shift in the position of the bubble tube. The corrected 1979 CW water levels were higher (about 5 ft) than the NW water levels, especially when basins 2 and 3 were flooded at the same time and groundwater mound formation in the center of the project was most pronounced. General fluctuation patterns for both wells were fairly well in phase.

Of the three new wells in the center of the project, water levels were highest in 60W and lowest in 100W (Fig. 9). This indicates that the hydraulic head decreases with depth in the center of the project, particularly when basins 2 and 3 are flooded and there is more downward flow in the aquifer at the center of the project than when basins 1 and 4 are flooded. Thus, the water level elevations in the three wells differed more on 18 December when basin 3 was just dried and basin 2 was just flooded than on 31 December when basin 1 was flooded only. As a whole, the water levels in 60W, 80W, and 100W were about 5 ft higher than those measured in CW (see Fig. 7).

Figure 9 shows the north-south water level profile as measured in SW, 60W, 80W, 100W, and NW. SW and NW are about 670 ft from the center of the project. The water levels of 60W, 80W, and 100W should have been plotted on the centerline of Fig. 9, but they were separated by 0.1 in. on the graph to better show the individual water levels. Figure 9 shows that the groundwater gradient is predominantly from the south to the north. On 21 and 27 December, there was also flow to the south from the center of the project, as could be expected if the static groundwater table were essentially level and there would be little groundwater movement other than that caused by the recharge from the infiltration basins. The southward flow from the center of the project could be an aftereffect of the flooding of basins 3 and 4, which may have created more groundwater mounding below the south half of the project. More measurements of water level elevations in the wells will be made in 1980.

I.3. Quality of effluent and renovated water

Nitrogen. The total nitrogen content in the secondary effluent from the 23rd Ave. Sewage Treatment Plant generally ranged between 13 and 26 mg/ℓ (Fig. 10) and averaged about 18 mg/ℓ. Almost all of the nitrogen in the effluent was in the ammonium form.

Renovated water from the NW, which is just north of basin 1, showed the characteristic NO_3-N peaks when water that infiltrated at the beginning of a flooding period reached the intake of the well (Fig. 11). This water generally has a high NO_3 content because it has leached out nitrates from the upper few feet of the soil that were formed there during drying. The center of the NO_3 peak in the beginning of November occurred 7 days after the start of the preceding flooding period, which was on 26 October. The center of the NO_3 peak in the first half of December occurred about 12 days after the start of the next flooding period, which was 27 November. Since the average infiltration rate for the 26 October flooding period was 1 ft/day and for the 27 November flooding period 0.6 ft/day, it should take the effluent water 1/0.6 times as long to travel from basin 1 to the NW for the 27 November period as for the 26 October period. According to this, the arrival time of the nitrate peak for the 27 November flooding period should be $1/0.6 \times 7 = 11.7$ days. This agrees with the observed period of 12 days. If the infiltration rate during the flooding period that started 27 November had also been 1 ft/day, the center of the nitrate peak would have arrived at the NW 7 days after the start of flooding and the time period between the centers of the NO_3-peaks would have been 28 days. This agrees with the actual time period of 31 days between the start of the 26 October and 27 November flooding periods. Thus, it is concluded that the NO_3-N peaks in November and December of Fig. 10 correspond to the flooding periods starting 26 October and 27 November, respectively.

The travel time of the nitrate peak of 7 days at an infiltration rate of 1 ft/day is quite small, and it implies a minimum average macroscopic velocity of 70/7=10 ft/day (assuming direct vertical flow from the infiltration basin to the intake of the well). The water table in the November-December period was about 40 ft below the bottom of the basins. Thus, the water had to travel through an unsaturated zone of 40 ft and then an additional 30 ft through the aquifer before reaching the bottom of the North well. If θ represents the volumetric water content of the vadose zone, the downward velocity in this zone at an infiltration rate of 1 ft/day is about $1/\theta$ ft/day. The time it takes to reach the 40-ft deep water table then is equal to 40θ days. Assuming that the water content in the aquifer is twice the water content in the vadose zone, the time for the water to travel the 30 ft in the aquifer can similarly be calculated as $30 \times 2\theta$ days. Since the total travel time is 7 days, we have $40\theta + 60\theta = 7$, from which θ is calculated as 0.07. According to this, the water content in the vadose zone would be 7% and in the aquifer 14%. These figures could be reasonable, considering that the underground materials contain a lot of gravel and that the voids between the gravel particles are filled with sand. Assuming that the individual porosities of the gravel and the sand as such are both 40%, the porosity of the medium as a whole would be 40% of 40%, or 16%. This is close to the 14% calculated above.

The NH_4-N content of the water from NW was below 1 mg/ℓ and averaged 0.62 mg/ℓ. The average concentration of NO_2-N in the NW water was 0.045 mg/ℓ, and that for organic N 0.185 mg/ℓ.

For the Center well water, NO_3-N contents generally ranged between 5 and 8 mg/ℓ with an average of 6.33 mg/ℓ (Fig. 12). NH_4-N concentrations were below 1 mg/ℓ and often close to zero. The average NH_4-N concentration was 0.12 mg/ℓ. Average concentrations of the other forms of nitrogen were 0.04 mg/ℓ for NO_2-N and 0.19 mg/ℓ for organic N.

Since the CW is perforated from 100 to 180 ft, the water from the well is a mixture of renovated waters that have infiltrated at various parts in the basins and have had different times and distances of underground travel. Hence, individual NO_3-peaks as in Fig. 11 are not present and the NO_3-N values are more uniform. Since the average total-N concentration in the effluent was about 18 mg/ℓ, the nitrogen removal is about 61%.

The NO_3-N concentrations in CW water are about the same as those in the NW water. This and other similarities in chemical parameters (see, for example, TOC, TDS, and fecal coliforms) indicate that most if not all of the water pumped from the CW is renovated sewage effluent and not native groundwater. The PO_4-P content of the CW water is lower, but this could be due to additional immobilization of phosphate as the renovated water moves deeper through the aquifer.

Phosphorus. PO_4-P concentrations in the secondary effluent generally ranged between 2 and 12 mg/ℓ and averaged about 6 mg/ℓ (Fig. 13). PO_4-P concentrations in the renovated water from NW generally were between 1 and 1.5 mg/ℓ (Fig. 11) and averaged 1.5 mg/ℓ. Interestingly, the renovated water exhibited PO_4 peaks that coincided with the NO_3 peaks and, hence, were associated with effluent water that infiltrated at the beginning of a flooding period. PO_4-P concentrations in the water from CW were more uniform (Fig. 13) and averaged 0.32 mg/ℓ. This is lower than the PO_4-P concentrations in renovated water from the NW. However, since the CW is much deeper than the NW, additional precipitation of phosphate deeper in the aquifer can be expected.

Total organic carbon. TOC concentrations in the secondary effluent generally ranged between 8 and 15 mg/ℓ (Fig. 14) and averaged 11.2 mg/ℓ. In the renovated water, TOC concentrations were more uniform and averaged 2.4 mg/ℓ for water from NW, and 2.0 mg/ℓ for water from CW. Identification of trace organics in renovated water from soil columns showed a wide range of compounds (see 1979 Annual Report by J. C. Lance).

Total dissolved solids. TDS-concentrations in the secondary effluent generally ranged between 650 and 900 mg/ℓ (Fig. 15) with an average of 756 mg/ℓ. The TDS concentrations in water from NW were similar to those in the effluent water. The same was true for TDS in CW water, except one low value (690 mg/ℓ) on 12 December.

Suspended solids. Suspended solids concentrations in the sewage effluent entering the basins averaged 9.6 mg/ℓ. The suspended solids content of the secondary effluent leaving the basins at the outflow ends (Fig. 1) generally was slightly lower (Figs. 16, 17, 18, and 19). This was due to settling of suspended solids in the infiltration basins. Occasional increases in suspended solids contents were also observed as the secondary effluent passed through the infiltration basins (see, for example basins 1, 2, and 3). This was due to growth of algae in the deeper and more stagnant areas near the outflow structures. Suspended solids contents for the renovated water averaged 4.3 mg/ℓ for NW and 0.5 mg/ℓ for CW.

pH. pH values were quite uniform and averaged 7.1 for the secondary effluent, 6.8 for the renovated water from NW, and 7.0 for CW.

Fecal coliform bacteria. Previous work has shown that the effluent from the Phoenix sewage treatment plants, which is not chlorinated, generally contains on the order of 10^5 to 10^6 fecal coliforms per 100 mℓ. Fecal coliform concentrations in the renovated water were much lower and often zero (Fig. 20). Average concentrations were 1.25/100 mℓ for

NW water and 2.3/100 mℓ for CW water. Presence of fecal coliforms in renovated water from the sampling wells probably is associated with the arrival of water that infiltrated at the beginning of a flooding period and in the portion of the basin that is closest to the well. Sampling of renovated water for virus assays is planned for early January 1980, using NW and 60W.

II. MESA PRIMARY EFFLUENT PROJECT

Field studies using primary sewage effluent were continued at the Mesa Sewage Treatment Plant (see 1977 and 1978 Annual Reports). The main objective was to determine the optimum operating conditions for maximum hydraulic loading. Four rectangular basins, 10 ft by 30 ft each, were used. The quality of the renovated water was not determined because of unreliable results obtained with samples from porous ceramic cups during 1978. The infiltration basins were too small for effective sampling of renovated water from the underlying aquifer.

II.1. Infiltration Rates

The infiltration schedule was 1 week flood and 1 week to 2 weeks dry. Equipment malfunction resulted in longer dry-ups at times. The Mesa Sewage Treatment Plant was shut down from February to the first part of April, resulting in a long dry-up during this period. The study was stopped at the end of August. Basin 3 was not used during 1979. The infiltration rates for basins 1, 2, and 4 are shown in Figures 21 to 23. There appeared to be little infiltration increase in basin 1 due to the long dry period in February and March. Raking the surface of basin 1 before the first inundation in April did not restore the infiltration rate to values observed during the previous year. Raking only breaks up the top 1 or 2 cm. The top 15 cm of basin 1 and 2 were broken up by rototilling. This increased the infiltration rate 3 times for basin 1 and 1.5 times for basin 2. The rate in basin 1 remained relatively high for the rest of the inundation periods, and averaged 1.5 ft/day. The rate for basin 2 was 0.83 ft/day for the first inundation period but decreased to about 0.6 ft/day at the end of August. Raking did not appear to be effective during this time period. Basin 4 was covered with a 2-inch layer of sand on the soil surface and was not rototilled. Raking the surface had no effect on the infiltration rate, which averaged 0.46 ft/day. The infiltration recovery due to the deeper tilling indicates that the depth of clogging was greater than 1 to 2 cm. The suspended solids in the primary effluent contain ferrous sulfide, which forms a very fine precipitate. The ferrous sulfide could have moved into the soil resulting in clogging with depth, rather than just surface clogging. An infiltration schedule of 1 week flood and 1 to 2 weeks dry-up, with the longer dry-up during the cold winter months, thus would result in a loading rate of 100 to 200 ft/yr. Periodic scarifying of the top

15 cm of soil was required to maintain adequate infiltration. Infiltration basins with primary effluent thus required more maintenance than those with secondary effluent.

III. SLUDGE COLUMNS

Sandy soils (dune sands, floodplains, etc.) generally are not the best soils for rapid infiltration systems because their infiltration rates are too high for effective treatment of the sewage water and their cation exchange capacity (CEC) is too low for adsorption of ammonium during flooding. The latter will result in poor nitrogen removal from the sewage water. Virus immobilization is also dependent upon adsorption and infiltration rate. Adding sewage sludge to these sands could produce two results: (1) the infiltration rates could be reduced to values that would be suitable for effective land treatment, and (2) the CEC would be increased. These effects were studied on laboratory soil columns.

Eight columns, 1.5-m long and 10 cm in diameter, were constructed from PVC plastic pipe. The columns were filled with 6 cm of pea gravel and 165 cm of No. 70 silica sand. The sand was packed to an average bulk density of 1.65 g/cm^3. The hydraulic conductivity of the sand was 6.2 m/day. The top 20 cm of each column was then packed with different sludge and sand mixtures. Dry sludge from the 23rd Avenue Plant was further dried, crushed, and sieved through a 2 mm sieve. Two columns contained sand with no sludge and were used as a control. The sludge additions in the top 20 cm of the sand in the other columns were 3.7, 22.5, and 67.9 grams per hundred grams of sand, which represents 3.6, 14, and 40% sludge in the top 20 cm. Each rate was duplicated. Secondary effluent from the 23rd Avenue sewage treatment plant was applied to the columns at a cycle of 9 days flooding and 5 days drying, using a water depth of 10 cm. The flow rate was measured by weighing the accumulated column effluent at regular time intervals. Sewage water and column effluent were analyzed for NO_2, NO_3, NH_4, TOC, PO_4, and organic N.

III.1. Infiltration rates

The infiltration rates for the different columns are shown in Table 3. The sludge did not appear to have an effect on infiltration rate, except at the highest addition of sludge. After the first inundation period, the columns with the most sludge (67.9 g/100 g sand) became plugged and never regained infiltration capacity. Entrapped gases were the probable cause of infiltration reduction. No gases were expelled from these columns at the start of the inundation periods; however, gas bubbles were observed escaping from all other columns. A gas sample taken from one of the soil columns at a depth of 5 cm had 9% methane and 12% carbon dioxide concentrations. This high amount of CO_2 and CH_4 indicated a considerable amount of biological activity in the sludge-sand mixture.

The infiltration rates in the other 6 columns started at about 2.8 m/day and decreased with each inundation period. There was a slight infiltration increase in the 22-30 August period due to a month-long dry up. On 18 December the surface was broken up and the infiltration rates for the next inundation period were nearly the same as those of the initial period. Thus, decreases in infiltration rate were due to surface clogging. On the other hand, scratching the surface of the high-rate sludge columns did not increase the infiltration rate, which led to the conclusion that the infiltration rate in these columns was reduced by accumulation of gas in the sand-sludge mixture.

III.2. Cation exchange capacity

The addition of sludge did increase the CEC as shown in Figure 24 where the CEC in meq/100 g soil is plotted against the ratio of sludge to sand by weight. The percentage organic carbon in the sand-sludge mixture is also shown in Figure 24. The CEC decreased by a factor of 2 after several flooding cycles. Most of this decrease probably occurred in the first few flooding cycles as the more soluble organic carbon was decomposed and leached out. High total organic carbon (TOC) concentrations were observed in the outflow from the columns containing sludge during the first two cycles. The CEC was not adequate to adsorb the large amounts of ammonium that entered the soil with the high infiltration rates. During the last two cycles, however, when the infiltration rate was low, most of the ammonium was adsorbed. The infiltration rates during this time period were between 6 and 26 cm/day. Columns with sand only showed a similar adsorption of ammonium, however.

III.3. Nitrogen removal

The percent nitrogen removal, expressed in milligrams per flooding cycle is shown in Table 3. The average removal was essentially the same for each treatment during the first few cycles, as shown in Figure 25. The columns were dry for 5 weeks during August because of an electrical malfunction. When the columns were flooded again a large flush of nitrate was observed in the column effluent. Nitrogen removal was greatest during the first inundation period when the infiltration was also the greatest. First about 400 mg per cycle was removed. This decreased to 150 mg per cycle after three cycles. After the long dry up, the nitrogen removal was about 200 mg per cycle, and after four cycles it was between 100 and 180 mg per cycle. As the infiltration decreased the total nitrogen removal decreased, but the percent nitrogen removal increased. This is shown in Figure 26. There appears to be no beneficial effect from the sludge on removing nitrogen. The infiltration rates continually decreased from the first inundation period and did not stabilize with time. The continual change in infiltration rate probably had a greater effect on the nitrogen removal than the sludge itself.

IV. INFILTRATION OF FLOOD WATER

Recent flooding of the Salt River has renewed interest in groundwater recharge with flood water. The high concentration of suspended material is the dominant factor that determines the infiltration rate of flood water. Laboratory studies were conducted to get an estimate of the effect of sediment concentration on infiltration rate decrease. Soil columns 6 cm in diameter and 12 cm in length were packed with coarse and fine sand, which had a hydraulic conductivity of 18 and 1.3 m/day, respectively. These sands are typical of surface material in the Salt River bed. Flood water from the river was applied to the columns. The apparatus is shown in Figure 27. The sediment load was kept in suspension by continuous stirring with a magnetic stirrer. Water was pumped out of the reservoir and into the columns. The overflow from the columns went back into the reservoir. The outflow from the columns was continually monitored by measuring the water level in the collection reservoir with a pressure transducer and recorder. The suspended load remained essentially constant for the infiltration period. Columns were run in triplicate or duplicate. Flood waters with suspended solids concentrations of .620, .425, and .014 g/ℓ were used on the fine sand, and of .600 g/ℓ on the coarse sand. The .014 g/ℓ represents the concentration of sediment left in the water after standing for 24 hours.

IV.1. Results and Discussion

Infiltration rates as a function of the total accumulated infiltration are shown in Figures 28 to 31 for the different runs. For the fine sand, the infiltration rate decreased rapidly at first and then slower as infiltration continued. The reverse was true for the coarse sand, where the infiltration rate decreased more rapidly as time progressed. Previous literature has indicated that the infiltration rate decreases linearly when plotted against accumulated infiltration according to the relation $I_t = I_o - \alpha C_s S_t$, where I_t = infiltration rate at time t (m day^{-1}), I_o = initial infiltration rate, α = clogging coefficient ($\ell\ day^{-1}g^{-1}$), C_s = suspended solids concentration, (g ℓ^{-1}), and S_t = accumulated infiltration at time t (m). The accumulated infiltration can be expressed as

$$S_t = \frac{I_o - I_o e^{-t\alpha C_s}}{\alpha C_s} \qquad (1)$$

The clogging coefficient must be experimentally determined for a given system. Once α is known, the infiltration rate and total infiltration in relation to time can be estimated.

The α values determined from Figures 28 through 31, are shown in Table 4. The α coefficients were between 6 and 13 $\ell\ day^{-1}g^{-1}$ at the start of infiltration for both coarse and fine sands at the 3 highest suspended load concentrations. As time progressed, the α values decreased in the fine sand but increased in the coarse sand. At the lowest suspended solids concentration of .014 g/ℓ, the initial α value was much higher (55 to 84 ℓ $day^{-1}g^{-1}$), but then decreased to about 11 ℓ $day^{-1}g^{-1}$ as time progressed. The lower α value at a constant suspended solids concentration indicates a lower clogging rate. The rate of infiltration reduction is a function of the initial infiltration rate and of the amount of solids that accumulates on the bottom. When the infiltration rate is high, more suspended material is deposited on the bottom, accelerating the clogging process. Also, the clogged layer tends to be more compact because of the higher seepage forces. This could explain the increase in α value for the coarse sand. The total infiltration can be estimated from Equation 1 using two α factors, one for the initial inundation period and another for the final period. The total infiltration values are calculated for the average conditions shown in Table 4 and the time when I_t was reduced by 95%. Initial period was 3 hours for the coarse sand and 12 hours for the fine sand. Infiltration of the settled flood water into the fine sand was about 6 times that of the unsettled flood water. The infiltration rate decreased more rapidly in the coarse sand, and the time before a 95% reduction in infiltration rate occurred was much shorter, on the order of 1 day compared to 3 days for the fine sand. However, the total infiltration was higher in the coarse sand because of the higher initial infiltration rate.

The α values determined in this study apply to the case where the suspended material is being deposited from the infiltrating water only. Under ponded conditions, clogging could be accelerated because most of the suspended load from the entire pond will settle out within 24 hours. The deposited material then derives from more water than has infiltrated. If the velocity of the water is such that the bottom is continually cleaned, the infiltration rate could be higher.

All three of the above conditions could exist at the same time. The high velocity in the main channel would keep the bottom clean in a flood channel. Near the sides where the velocity is lower but still fast enough to keep the material in suspension, the suspended material would be deposited with the infiltrating water. Ponded conditions would exist when side pools are filled at high stage and are isolated when the river level drops. Further studies are required to determine the effect of velocity in the channel on the infiltration rate of sediment-laden water.

SUMMARY AND CONCLUSIONS

The 12-year-old Flushing Meadows Project (6 basins of 1/3-acre each) in the Salt River bed West of the 91st Avenue Sewage Treatment Plant was heavily damaged by flooding in 1978 and 1979, and it was not reactivated. Infiltration at the 23rd Avenue Project (4 basins of

10 acres each) was resumed in June 1979, following construction of a bypass channel in the 80-acre pond upstream from the infiltration basins. Originally, the infiltration basins received the effluent through the 80-acre pond, but this produced algal blooms and increased the suspended solids content of the effluent water considerably. The main bloom organism was Carteria klebsii Dillworth. The algae clogged the bottom of the infiltration basins by formation of an algal "filter" cake and precipitation of calcium carbonate on the soil. The algae problem was alleviated with the bypass channel, which took the secondary effluent from the 23rd Ave. Treatment Plant directly into the infiltration basins. To minimize growth of algae also in the infiltration basins themselves, the water depths were kept rather small (about 8 inches) in the summer to achieve a higher rate of turnover of the effluent water in the basins. This reduced the exposure time of the water to sunlight and, hence, the growth of suspended algae.

Flooding and drying periods for the infiltration basins were 9 days each, except in winter when they were changed to 1 week flooding-3 weeks drying because of longer ponding in the low places and slower drying. Infiltration rates initially were on the order of 6 ft/day, but leveled off to an average of about 1.5 ft/day for the rest of the inundation periods. Accumulated infiltration for the last 6 months of 1979 was 125 ft, yielding a hydraulic loading rate of 250 ft/year. This figure probably can be increased to 300 ft/year by increasing the water depth in the basins during the winter months. Thus, the capacity of the four 10-acre basins probably is about 12,000 acre feet per year, which is equivalent to 11 mgd or 7640 gpm. The suspended solids content of the effluent water entering the infiltration basins averaged 9.6 mg/ℓ, while that of the water leaving the basins at the outflow end generally was slightly lower due to settling of suspended solids. Sometimes, however, this suspended solids content was also slightly higher due to algae growth near the outflow structure. Most of the algae growth in the infiltration basins was on the surface (mainly Chlamydomonas or Pandorina) or on the bottom (mainly Oscillatoria) -- the water itself remained quite clear.

Three additional observation wells (60, 80, and 100 ft deep, respectively) were drilled with the air-rotary method in the center of the project to allow better measurement of groundwater levels and their response to infiltration, and better sampling of renovated water from the top of the aquifer. The latter is particularly important for trace organics identification and virus assays. Depth to groundwater was about 30 ft in early summer and averaged about 40 ft for the rest of the year. Groundwater levels responded to infiltration from the basins. The natural slope of the water table generally was from South to North. The total nitrogen content averaged 18 mg/ℓ (mostly as ammonium) for the secondary effluent and 7 mg/ℓ (6.3 as nitrate) for the renovated water from the Center Well, yielding a nitrogen removal of 61 percent. The renovated water from the North Well showed characteristic NO_3-N peaks, which for an infiltration rate of 1 ft/day in the northernmost basin arrived one week after the start of a new flooding period. If it is assumed that the water content in the aquifer is twice that in the vadose zone, this arrival time indicates volumetric water contents of 14 percent in the aquifer and 7 percent in the vadose zone. The PO_4-P content averaged 6 mg/ℓ for the secondary effluent, 1.5 mg/ℓ for the 75-ft deep North Well, and 0.32 mg/ℓ for the Center Well which is perforated from 100 to 180 ft. PO_4-P peaks in the renovated water from the North Well coincided with the NO_3-N peaks in that water. Total organic carbon concentrations generally ranged between 8 and 15 mg/ℓ (average 11.2 mg/ℓ) for the secondary effluent, and averaged 2.4 mg/ℓ for the renovated water from the North Well and 2.0 mg/ℓ for that from the Center Well. Total dissolved solids contents were about the same for the secondary effluent and the renovated water. They averaged 756 mg/ℓ for the effluent. The suspended solids content averaged 4.3 mg/ℓ for the renovated water from the North Well and 0.5 mg/ℓ for that of the South Well. The pH of the effluent and renovated water was about 7. Fecal coliform concentrations averaged 1.25/100 mℓ for water from the North Well and 2.3/100 mℓ for water from the Center Well. The renovated water meets the standards of the Arizona Department of Health Services for unrestricted irrigation. Plans are being developed to drill additional wells for pumping renovated water and to deliver this water to an irrigation canal for unrestricted irrigation.

Studies on infiltration rates of primary effluent in 10 x 30 m basins in Mesa, AZ, were concluded in 1979. Low infiltration rates were observed in the colder winter months. Scarifying the surface 2 cm by raking did not adequately restore the infiltration rate, as it had in the past. Breaking up the top 15 to 20 cm by rototilling did increase the infiltration rate 1-1/2 to 3 times. An annual hydraulic loading rate of 100 to 180 ft could be expected by proper management of the infiltration basins This should include periodically scarifying the top 15 to 20 cm by harrowing or disking when the infiltration rates start to decrease. Thus, more infiltration basin maintenance is required when using primary effluent than when using secondary effluent.

A laboratory study was conducted to determine if sludge amendment to coarse sand would enhance nitrogen removal in rapid-infiltration systems for sewage effluent. Addition of dried sludge to sand columns increased the cation exchange capacity of the sand. The infiltration rate for secondary sewage effluent was not affected by the low rates of sludge addition. The usual decrease in infiltration rate during flooding was due to surface clogging. However, when the sludge concentration was 70 g per 100 g of sand, infiltration was reduced to essentially zero. This decrease was caused by entrapped gases produced by increased biological activity due to the high organic carbon and nitrogen content of the sludge. The increased cation exchange capacity did not result in increased nitrogen removal. The removal of nitrogen was primarily governed by infiltration rate and it was about the same for the sand with and without sludge amendment.

Infiltration of flood water containing high suspended loads (.400 to .600 g/ℓ) was studied in laboratory soil columns. Parameters were determined that would enable a more accurate determination of the reduction in infiltration rates due to sediment deposit on the bottom. The infiltration rates decreased rapidly when the high suspended load floodwater was applied to the soil columns. In coarse sand the infiltration rate decreased to 5% of the initial rate after 18 hours of flooding and 2 m of infiltration. The infiltration was essentially stopped after 1.2 days. The infiltration rate decreased more slowly in the finer sand; however, the total infiltration in a given time period was less because of the lower initial rate. Allowing the water to stand for 24 hours decreased the suspended load from .400 to .014 g/ℓ. The total infiltration for the settled flood water was about 6 times greater than that for the unsettled floodwater, and the time before 95% reduction in infiltration rates could be expected was increased from 3 to 15 days. Controlled groundwater recharge with floodwater using infiltration basins thus must include pre-sedimentation facilities for maximum effectiveness.

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1. Bouwer, Herman. 1979. Controlled Degradation and/or protection zones --Nonsense. Ground Water. 2:162-164.

2. Bouwer, Herman. 1979. Flow processes to underground from surface ponds. Proc. of Groundwater Recharge Symp., Phoenix, Az. Nov. 1978. pp. 1-12.

3. Bouwer, Herman. 1979. Geothermal power production with irrigation waste water. Ground Water. 17(4):375-384.

4. Bouwer, Herman. 1979. Reuse of sewage effluent in urbanizing irrigated valleys--Arizona's Salt River Valley. Proc. of the Water Use Symp. Washington, D. C. 3:2026-2033.

5. Bouwer, Herman. 1979. Soil-water hysteresis as a cause of delayed yield from unconfined aquifers. Water Resources Research 15(4):965-966.

6. Bouwer, Herman. 1979. Urbanizing irrigated valleys for Optimum Water Use. Jour. of the Urban Planning and Development Division 105(UP1):4150.

PERSONNEL: Herman Bouwer, Robert C. Rice, and Gladys C. Auer

Table 1. Elevation of wells and outflow boxes

Location	Place Surveyed	Elevation, ft. above sea level	Height of top of casing above ground, ft.	Sampling depth, ft.
North Well (NW)	Top of cover plate	1038.42	0.8	75
Center Well (CW)	Top of concrete base, east side	1037.58	1.3	100-180
Center Well (CW)	Metal base at probe hole	1038.06		
60-ft Well (60W)	Top of casing, north side	1038.90	2.9	60
80-ft Well (80W)	Top of casing, north side	1039.10	2.9	80
100-ft Well (100W)	Top of casing, north side	1039.10	2.9	100
South Well (SW)	Top of cover plate	1039.02	1.6	75
Outflow box Basin 1	Top of concrete, northeast corner	1035.62		
Outflow box Basin 4	Top of concrete, northeast corner	1035.43		

Table 2. Results of algae identification in samples from infiltration basins.

	July	November
INFLOW (EAST END)		
Surface	Ocsillatoria nigra Vaucher O. limnetica Lemmerman Chalamydomonas snowii Printz Oocystis parva West & West Unidentified (29μ diameter) sphaeroid cell Navicula sp. #1 Navicula sp. #2	
Plankton	Oscillatoria nigra Vaucher O. ornata Kuetzing Oocystis parva West & West Franceia ovalis Lemmerman Scenedesmus quadricauda Smith Marssoniella elegans Lemmerman Nephrocytium agardhianum Naegeli Scenedesmus incrassatulus Bohlin Chlorella sp. Sphaerocystis schroeteri Chordat Pandorina morum Bory Spondylomorum quarternarium Ehrenberg Stigeoclonium nanum Kuetzing Navicula sp. #1 Navicula sp. #3 Cryptomonas sp. Pandorina morum Bory [a] Carteria klebsii Dillworth [a]	
Bottom	Oscillatoria nigra Vaucher O. limnetica Lemmerman Navicula sp. #1	
OUTFLOW (WEST END)		
Surface	Oscillatoria limnetica Lemmerman Chlamydomonas snowii Printz Pandorina morum Bory	Carteria klebsii Dillworth Pandorina morum Bory Navicula sp. #1

[a] Main species in stagnant effluent at end of bypass channel with algae bloom. Carteria was the main bloom organism.

Table 2 (Continued)

	July	November
Surface (cont)	Scenedesmus opoliensis Richter Chlorella sp. Marssoniella elegans Lemmerman Oocystis parva West & West Stigeoclonium sp., germling Navicula sp. #1 Navicula sp. #2 Nitzschia sp. #1	
Plankton	Oscillatoria nigra Vaucher O. limnetica Lemmerman Oedogonium sp. Pandorina morum Bory Navicula sp. #1 Nitzschia sp. #1	Scenedesmus incrassatulus Bohlin Scenedesmus quadricauda Smith Merismopaedia (Agmenellum) tenuissima Pandorina morum Bory Nitzschia sp. #1 Oscillatoria nigra Vaucher Zygnema sp.
Bottom	Oscillatoria nigra Vaucher O. limnetica Lemmerman Pandorina morum Bory Sphaerocystis schroeteri Chordat Gloeocystis ampla Lagerheim Chlorella sp. Navicula sp. #1 Navicula sp. #2	Oscillatoria limnetica Lemmerman Oocystis parva West & West Scenedesmus incrassatulus Bohlin Nitzschia sp. #1

Table 3. Average infiltration rate, nitrogen loss, and percent nitrogen loss for sludge amended columns.

Start of 9-day flood period	Sand						3.7 g sludge per 100 g sand					
	Column 1			Column 7			Column 4			Column 5		
	I m/day	N loss mg/cycle	% N removal	I m/day	N loss mg/cycle	% N removal	I m/day	N loss mg/cycle	% N removal	I m/day	N loss mg/cycle	% N removal
15 May	3.20	--	--	2.81	--	--	1.64	--	--	2.41	--	--
29 May	2.26	--	--	2.57	--	--	2.98	--	--	2.57	--	--
12 Jun	1.36	319	14	2.16	408	11	2.31	624	14	1.81	355	12
26 Jun	0.49	239	24	0.88	340	22	1.15	191	9	1.24	325	15
11 Jul	1.06	152	10	0.75	170	17	1.35	179	9	0.93	147	11
22 Aug	1.42	-67	4	1.35	70	4	1.34	115	7	1.27	67	5
18 Sep	0.83	186	18	0.79	-104	-12	0.71	-100	-12	0.71	-79	-10
09 Oct	0.91	269	16	0.64	168	17	0.90	115	9	0.59	142	17
23 Oct	0.78	239	25	0.44	85	19	0.82	137	15	0.77	124	18
06 Nov	0.31	150	35	0.24	12	2	0.30	71	17	0.13	25	14
21 Nov	0.15	81	29	0.21	152	42	0.26	185	39	0.06	44	27
18 Dec	2.73	--	--	2.75	--	--	1.76	--	--	2.64	--	--

Table 3. Continued.

Start of 9-day flood period	22.5 g sludge per 100 g sand					
	Column 3			Column 6		
	I m/day	N loss mg/cycle	% N removal	I m/day	N loss mg/cycle	% N removal
15 May	1.97	--	--	2.47	--	--
29 May	2.84	--	--	2.99	--	--
12 Jun	2.03	327	10	2.71	509	11
26 Jun	1.12	263	14	1.68	295	10
11 Jul	1.20	242	14	1.60	62	3
22 Aug	1.31	-12	-1	1.09	39	3
18 Sep	0.96	199	17	0.40	260	24
09 Oct	0.91	273	19	0.98	210	15
23 Oct	1.33	288	14	1.63	201	11
06 Nov	0.39	203	39	0.88	300	26
21 Nov	0.07	-64	-39	0.17	108	33
18 Dec	2.66	--	--	2.28	--	--

Table 4. Suspended load, initial infiltration rate, and α factors for coarse and fine sand.

	C_s	I_o	α_1	α_2	S_t 1/
	g/ℓ	m/day	ℓ / day g		m
Coarse sand	.600	20.7	6.0	48.0	
	.600	16.7	5.8	12.8	
	.600	10.3	6.7	--	
Average	.600	16.0	6.0	30.0	2.20
Fine sand	.620	2.1	12.4	1.3	
	.620	1.9	13.5	1.8	
	.620	1.5	8.8	1.0	
Average	.620	1.8	11.6	1.4	.74
Fine sand	.425	3.1	6.2	2.6	
	.425	2.7	8.6	1.2	
	.425	2.5	7.2	1.4	
Average	.425	2.7	7.3	1.73	1.40
Fine sand	.014	1.7	84.0	11.00	
	.014	1.3	55.0	11.00	
Average	.014	1.5	70.0	11.00	6.00

1/ Calculated from Equation 1 for average values shown and when I_t/I_o = .05.

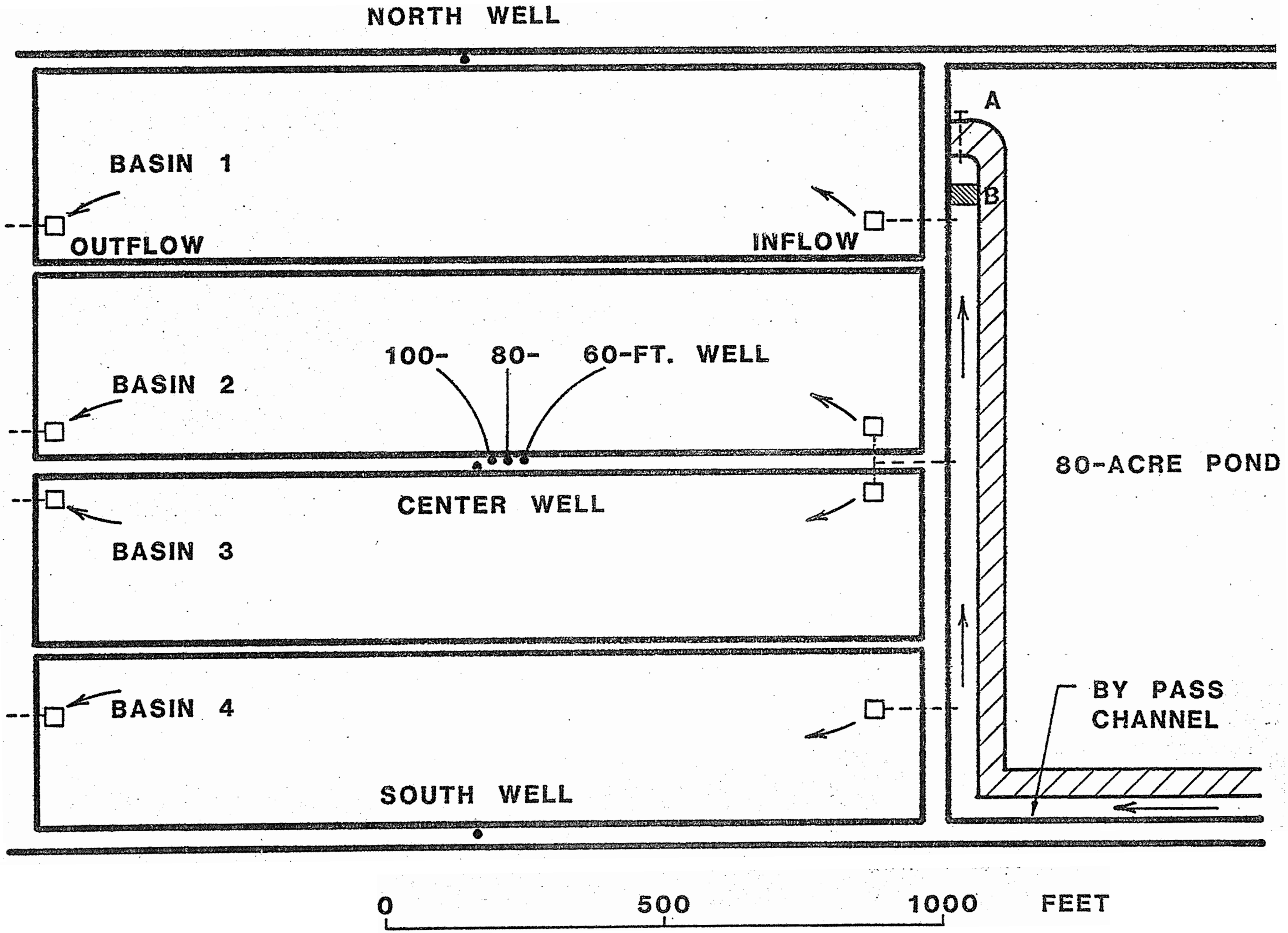


Figure 1. Schematic of 23rd Avenue Rapid Infiltration Project.

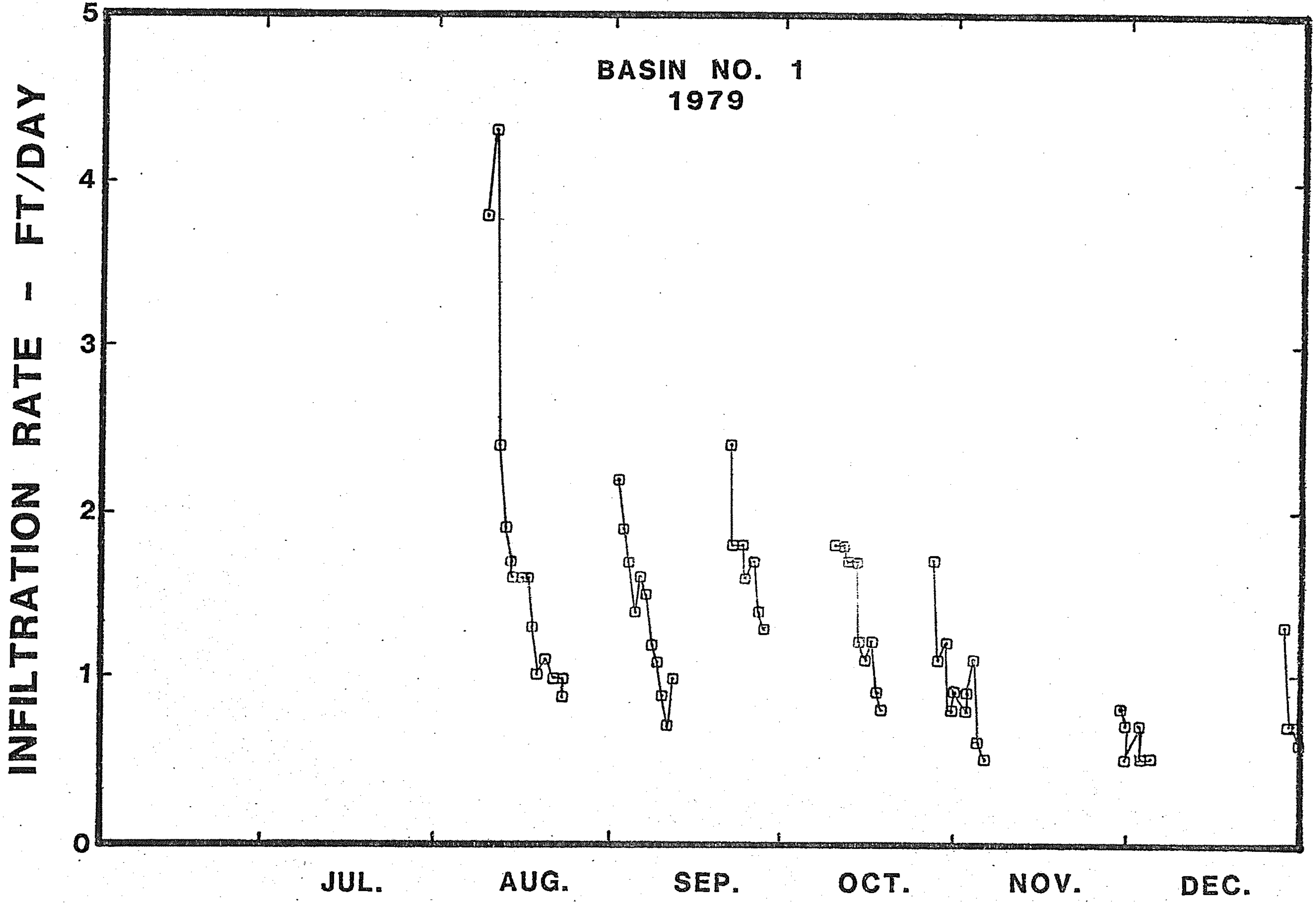


Figure 2. Infiltration rates for basin 1.

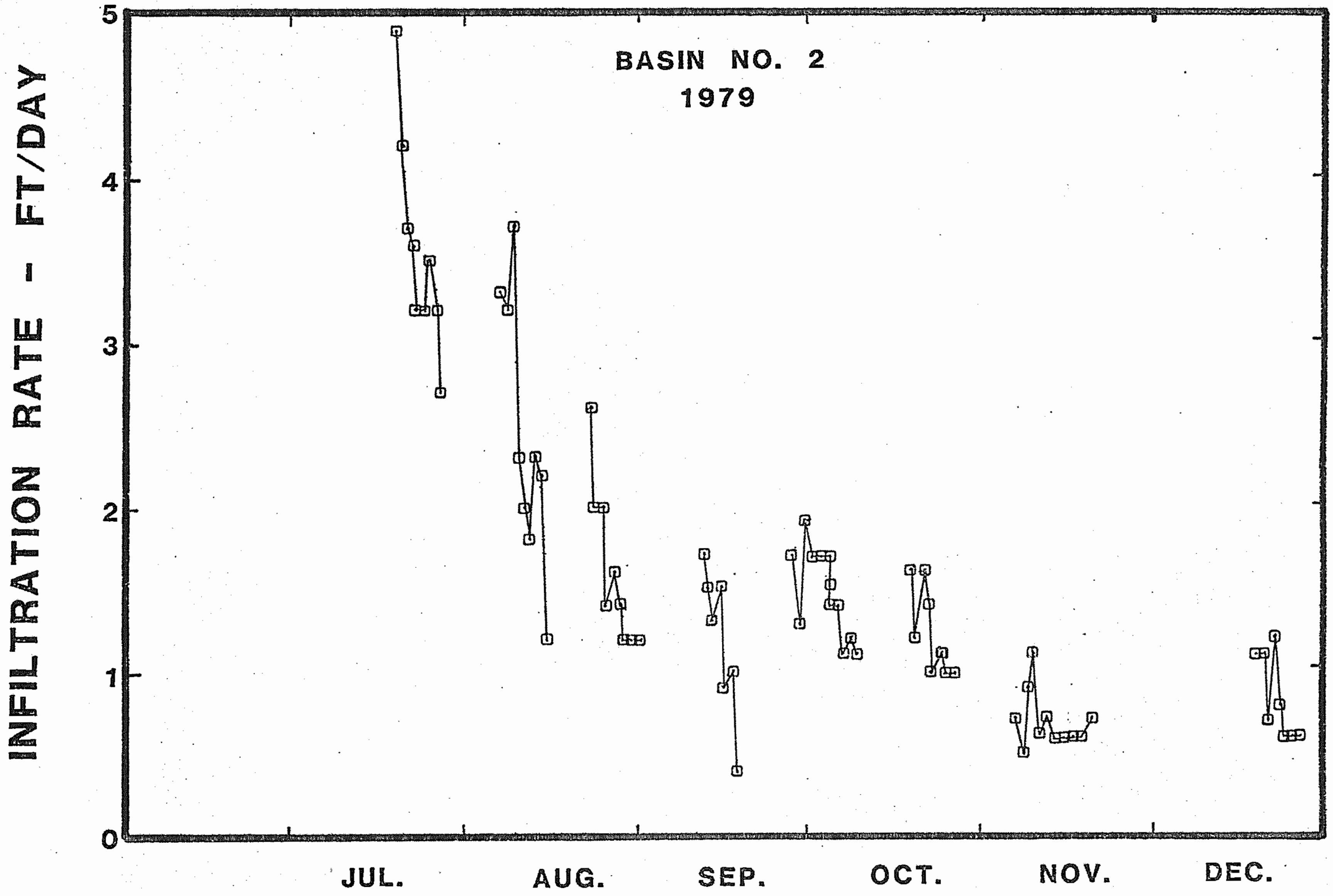


Figure 3. Infiltration rates for basin 2.

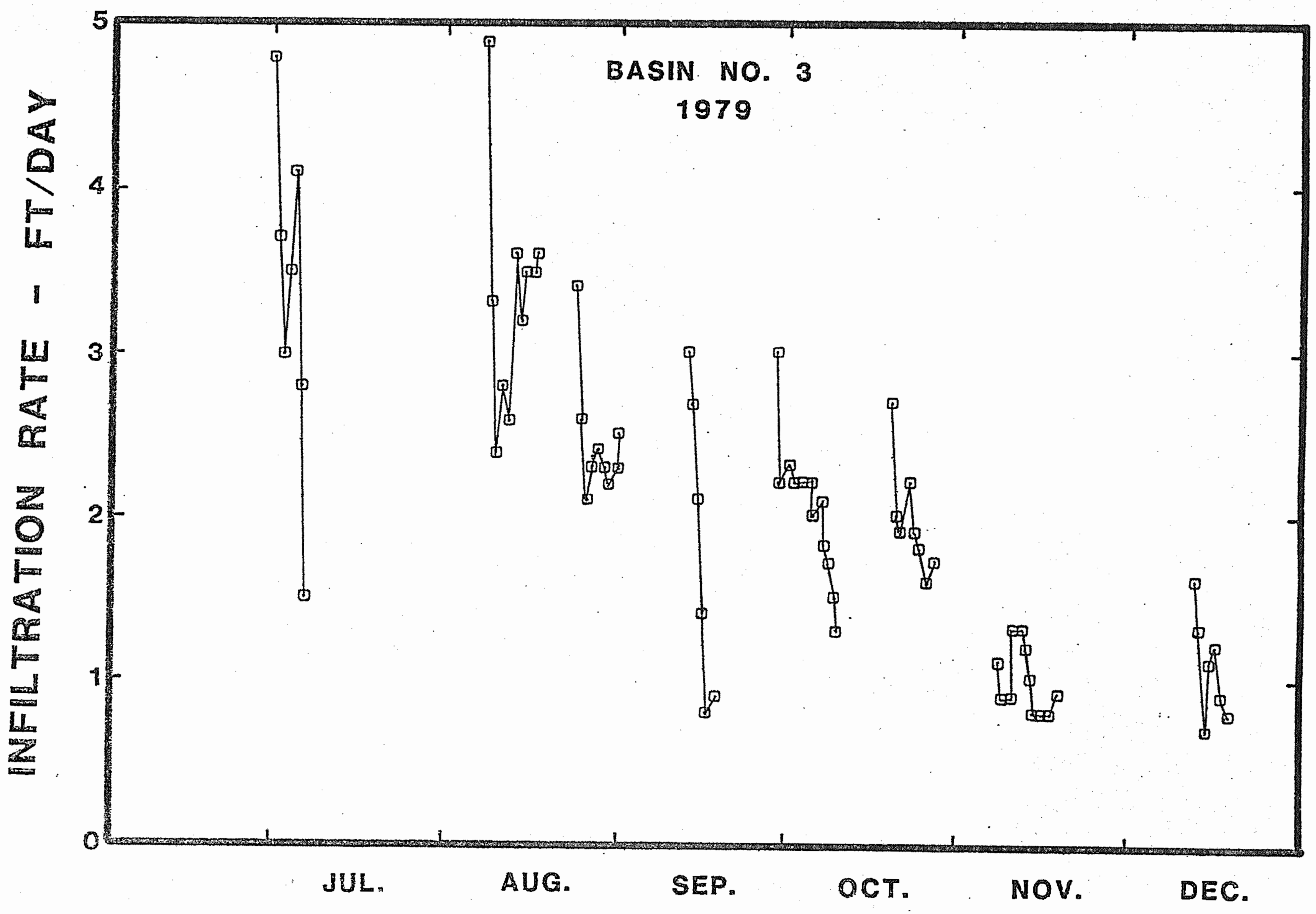


Figure 4. Infiltration rates for basin 3.

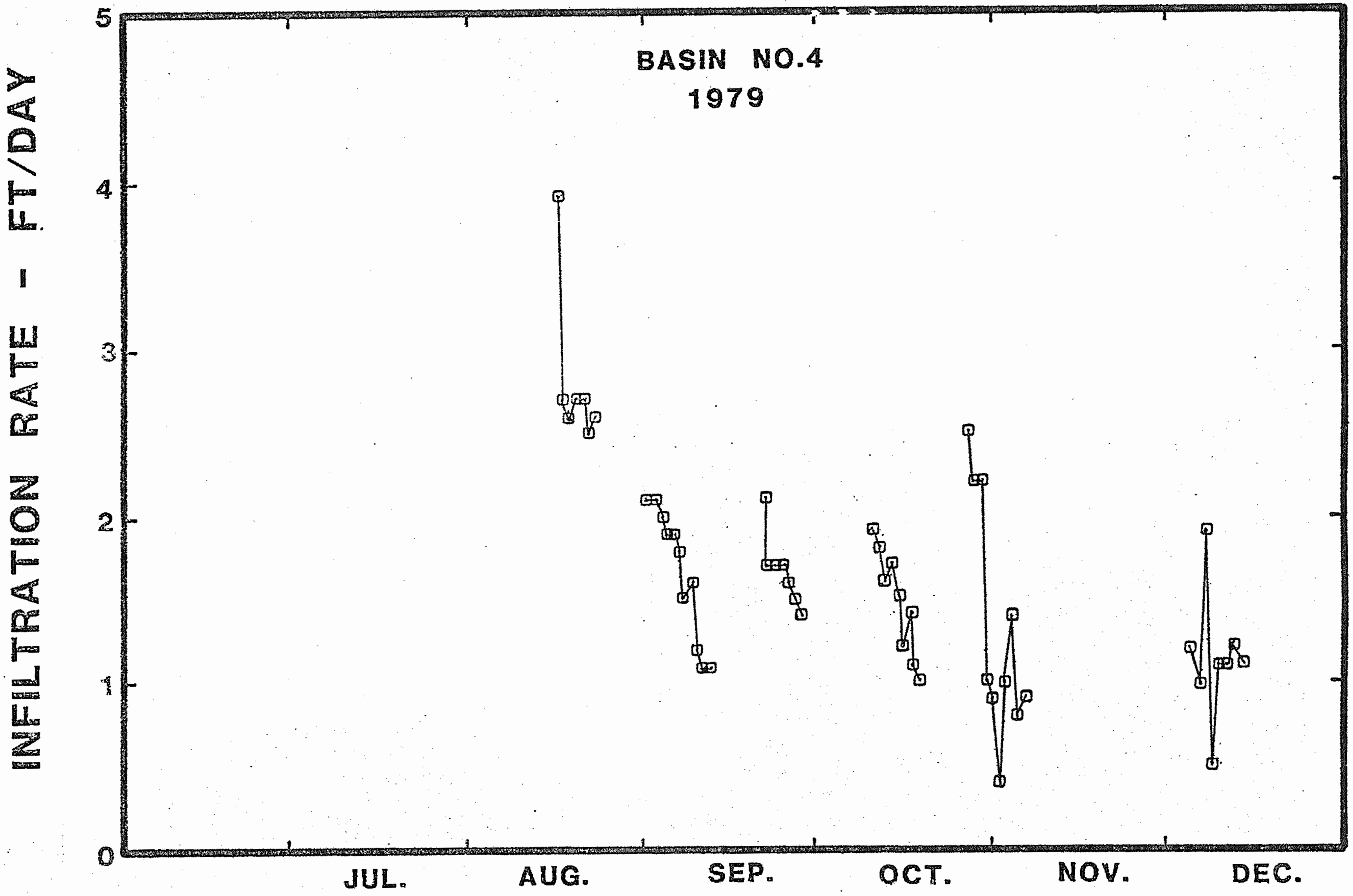


Figure 5. Infiltration rates for basin 4.

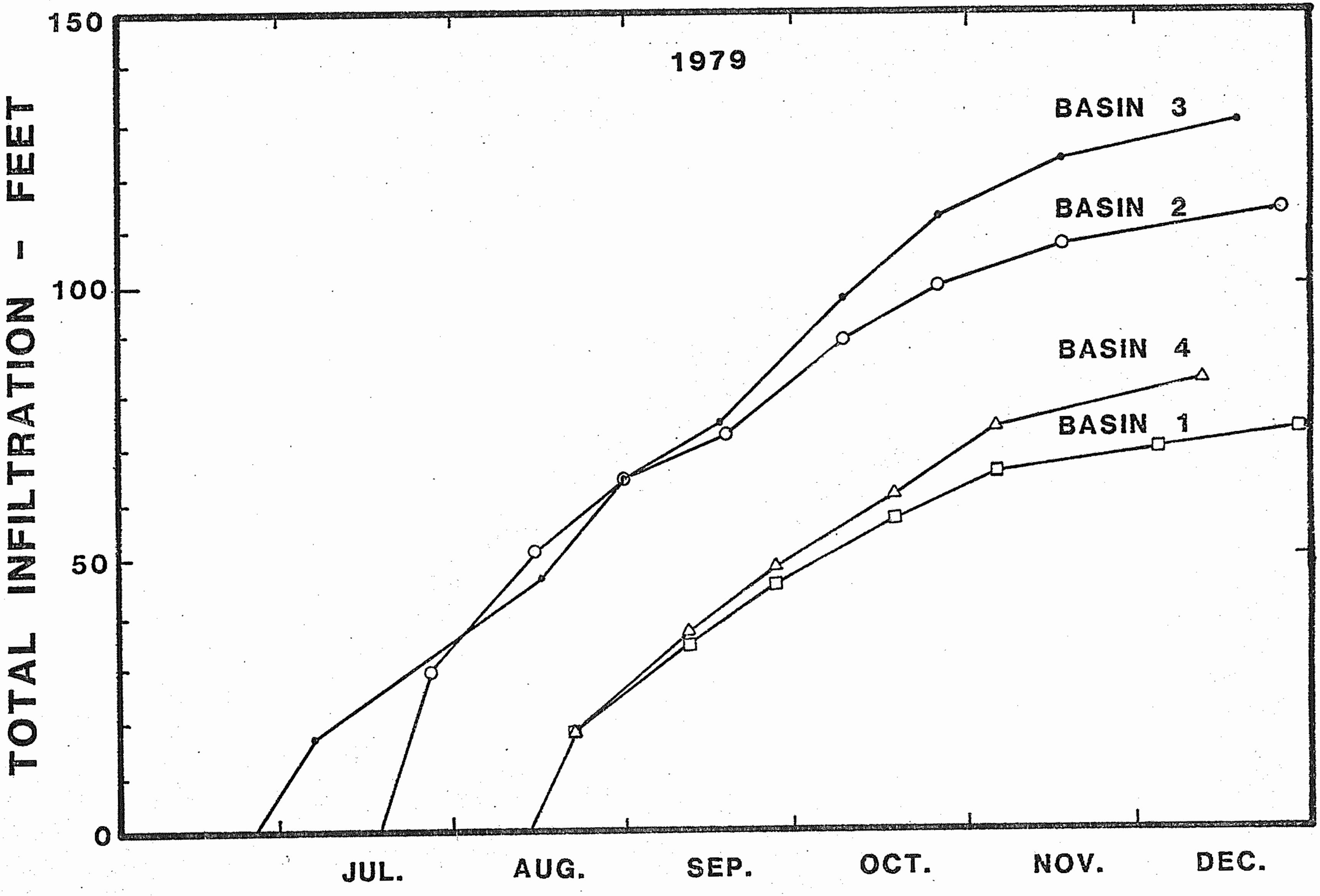


Figure 6. Accumulated infiltration rates for all basins.

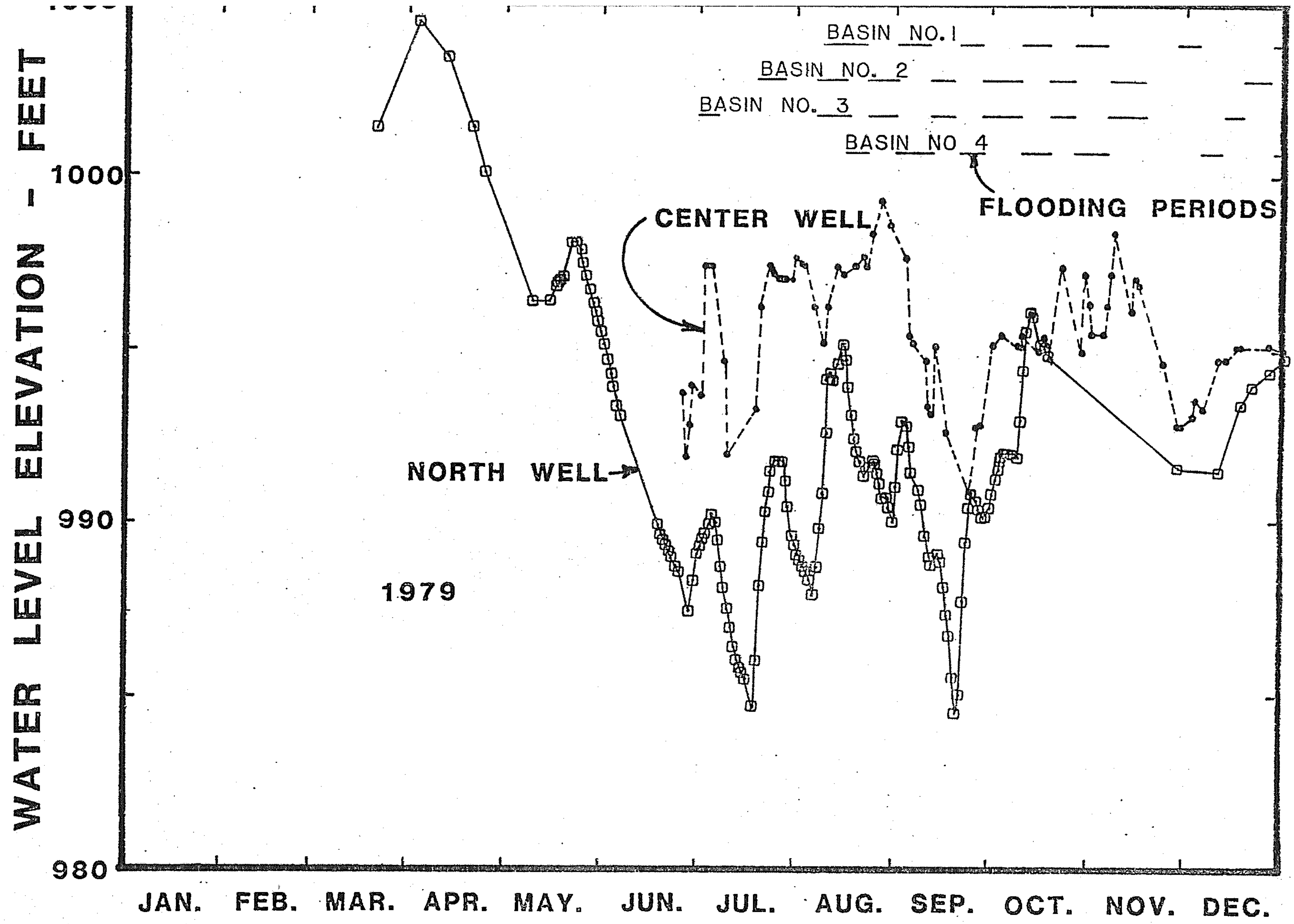


Figure 7. Water level elevations in NW and CW, and flooding and drying periods in infiltration basins.

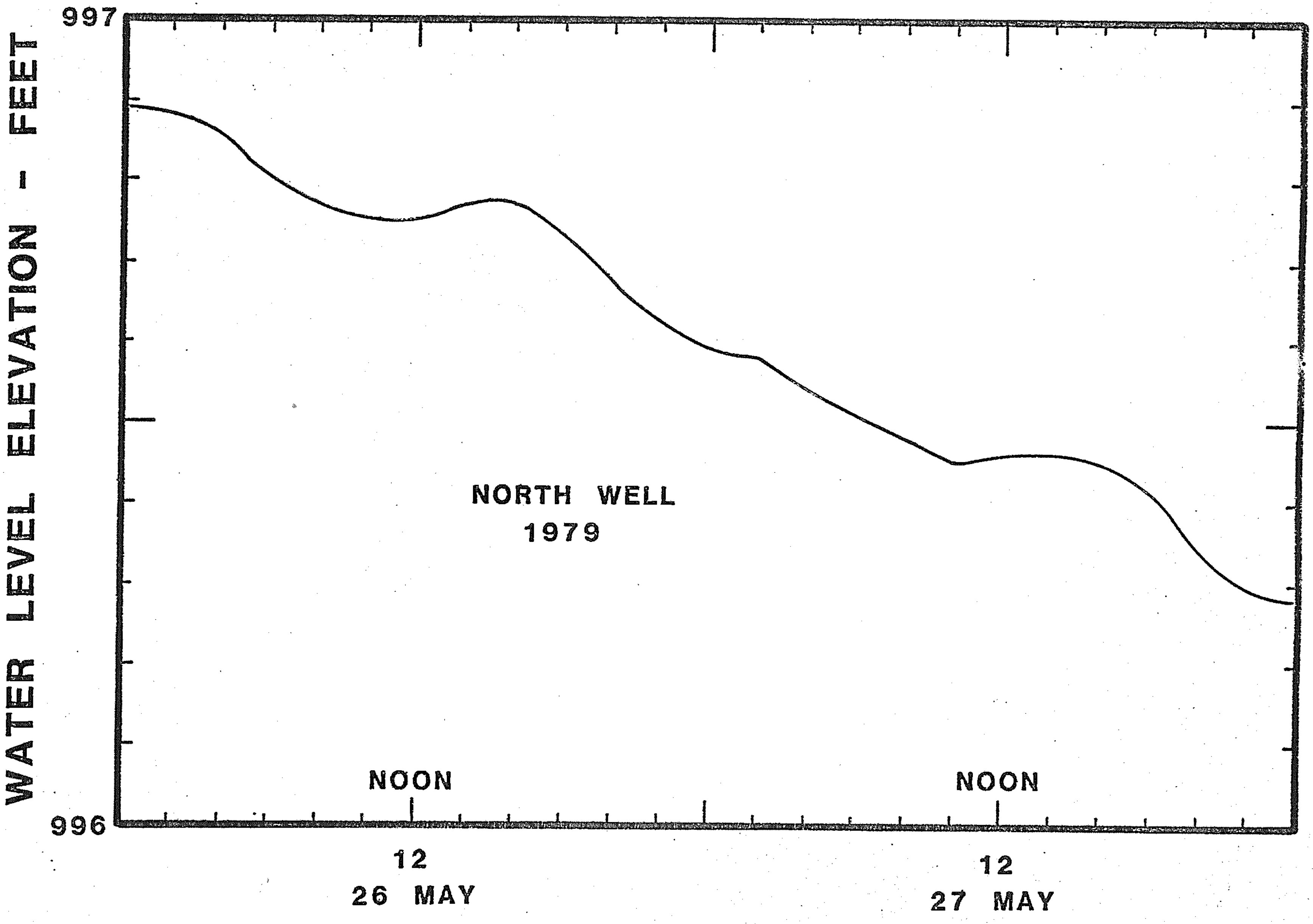


Figure 8. Example of diurnal water-level variations in NW.

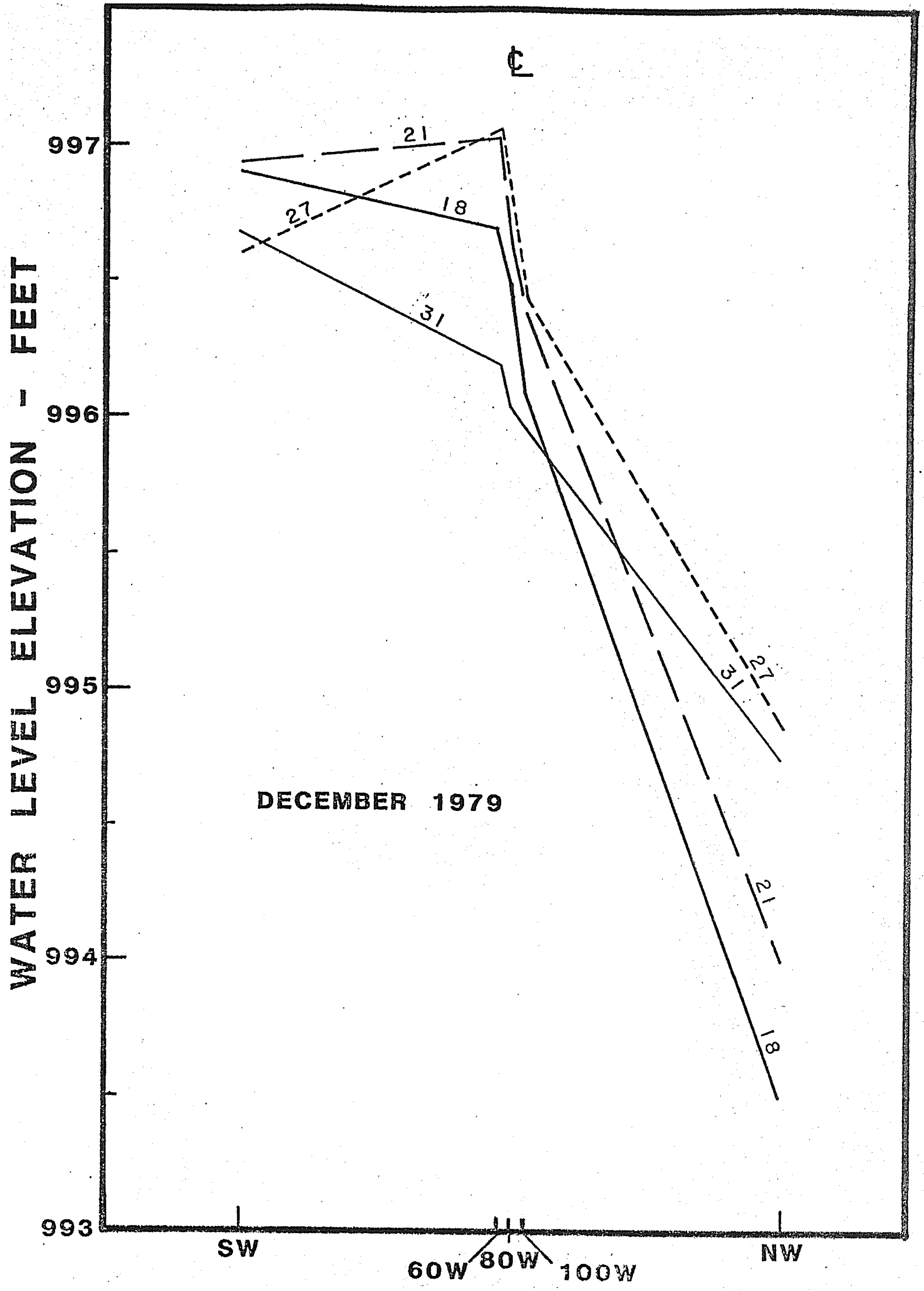


Figure 9. Groundwater level profile across basins in December 1979.

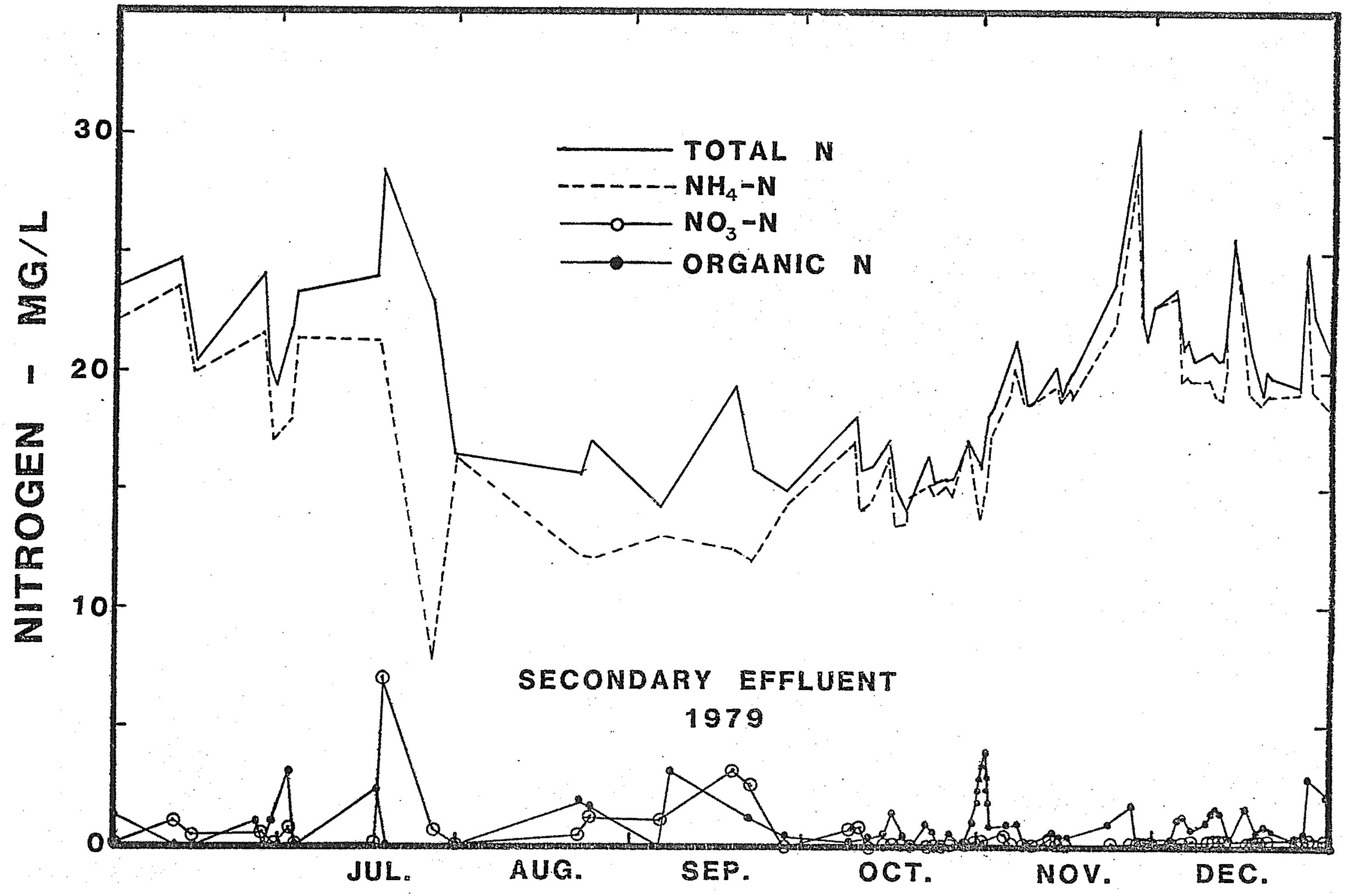
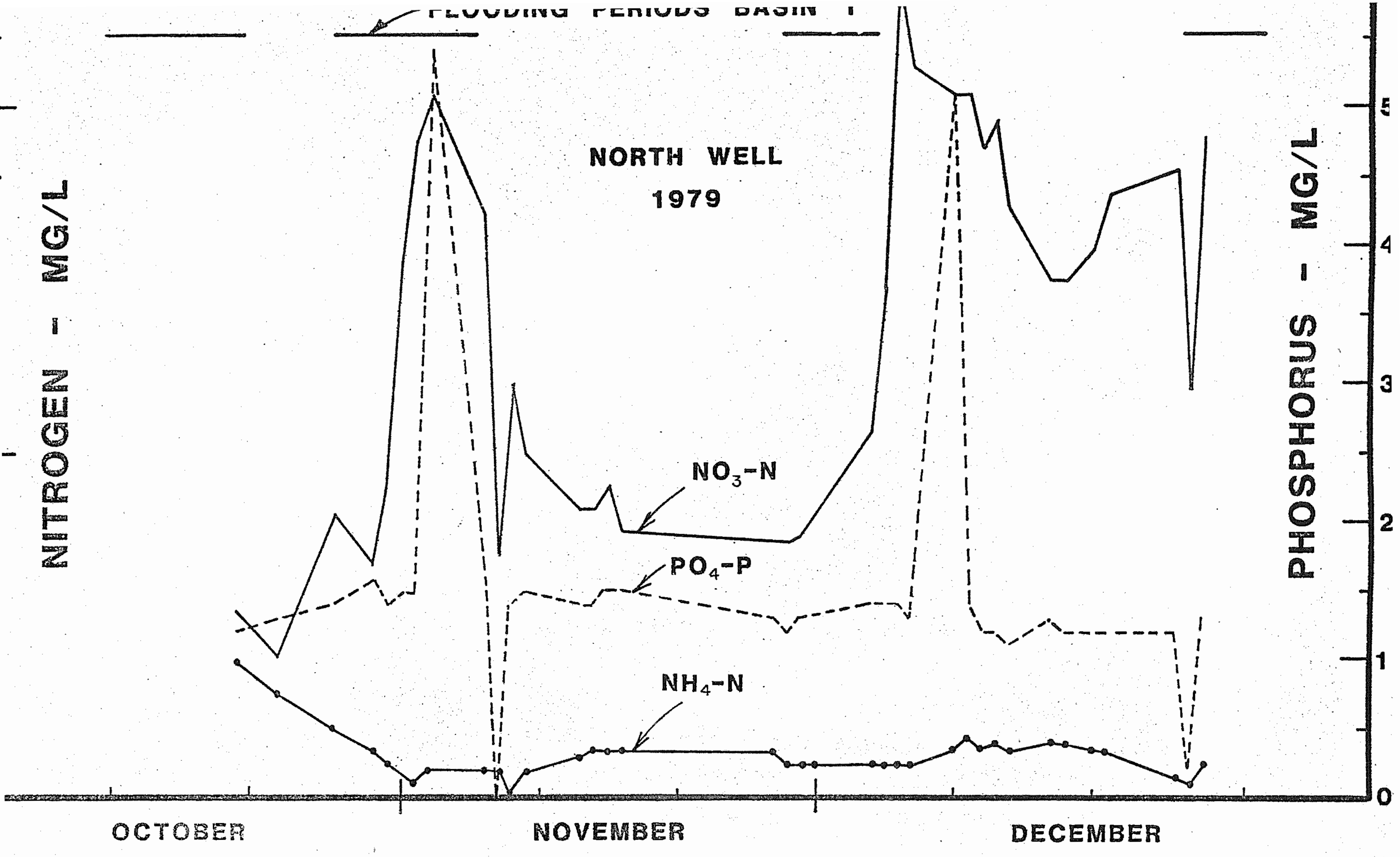


Figure 10. Nitrogen concentrations in secondary effluent from 23rd Avenue Sewage Treatment Plant.



igure 11. Nitrate-N, ammonium-N, and phosphate-P concentrations in renovated water from NW.

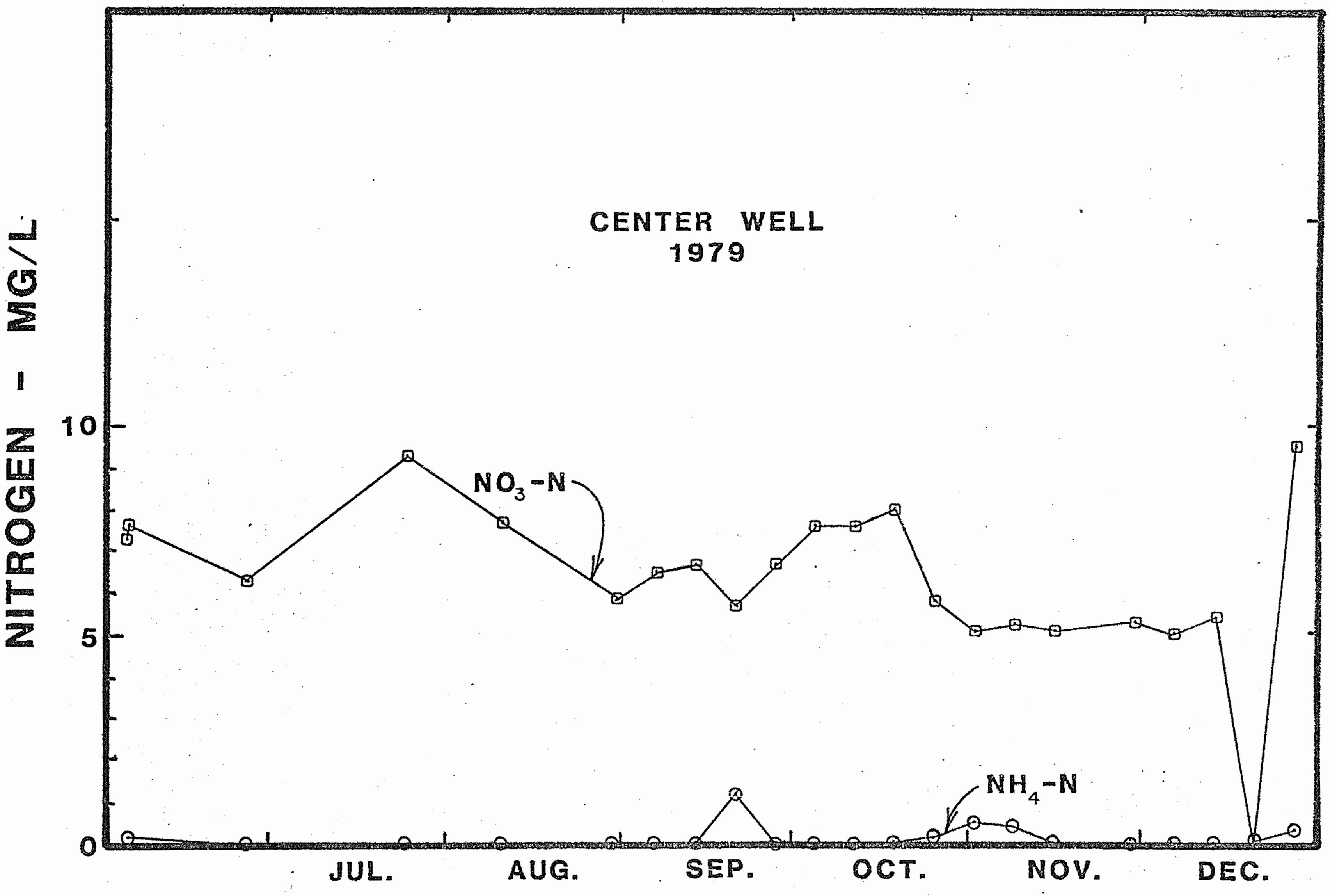


Figure 12. Nitrate-N and ammonium-N concentrations in renovated water from CW.

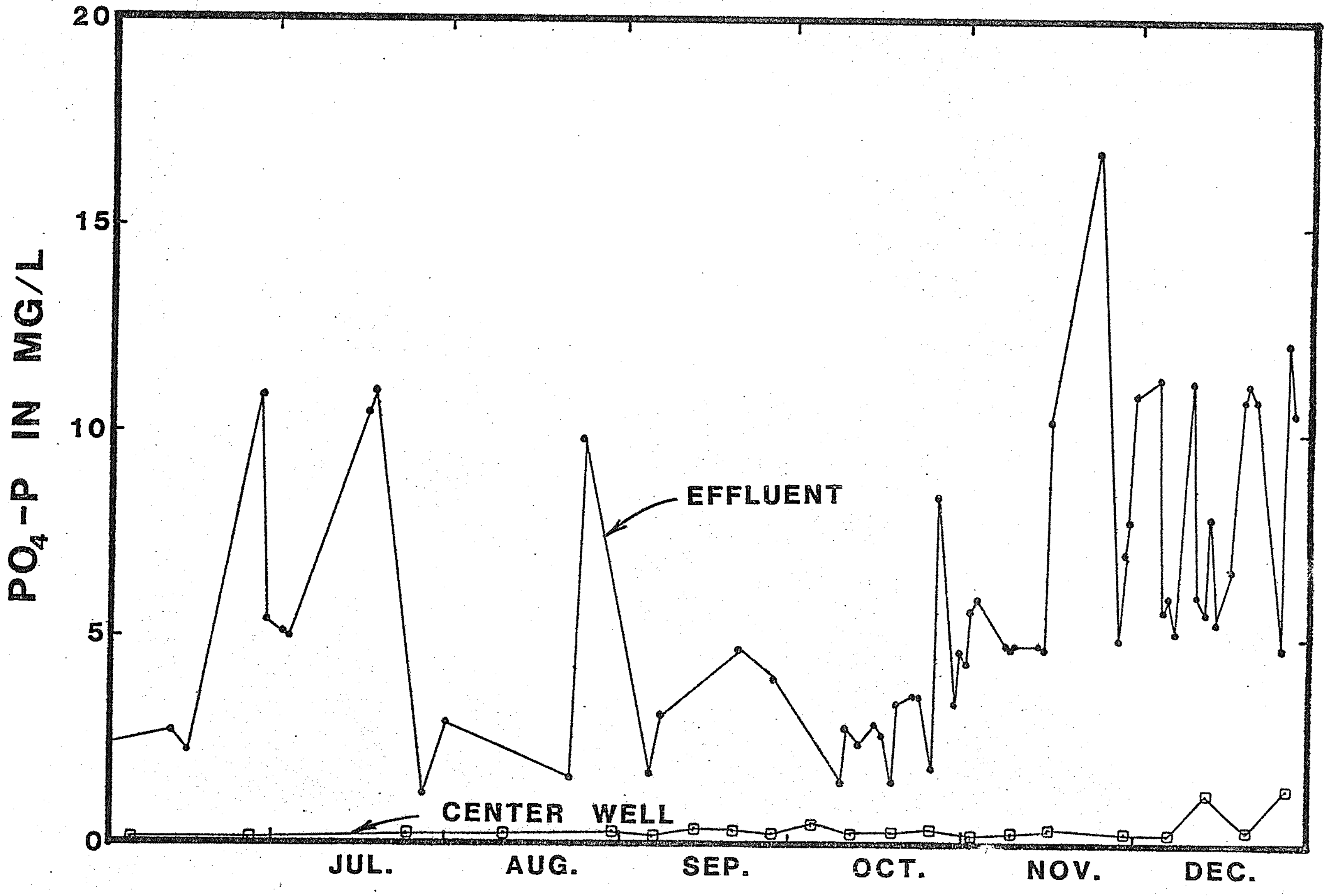


Figure 13. Phosphate-P concentrations in secondary effluent and renovated water from CW.

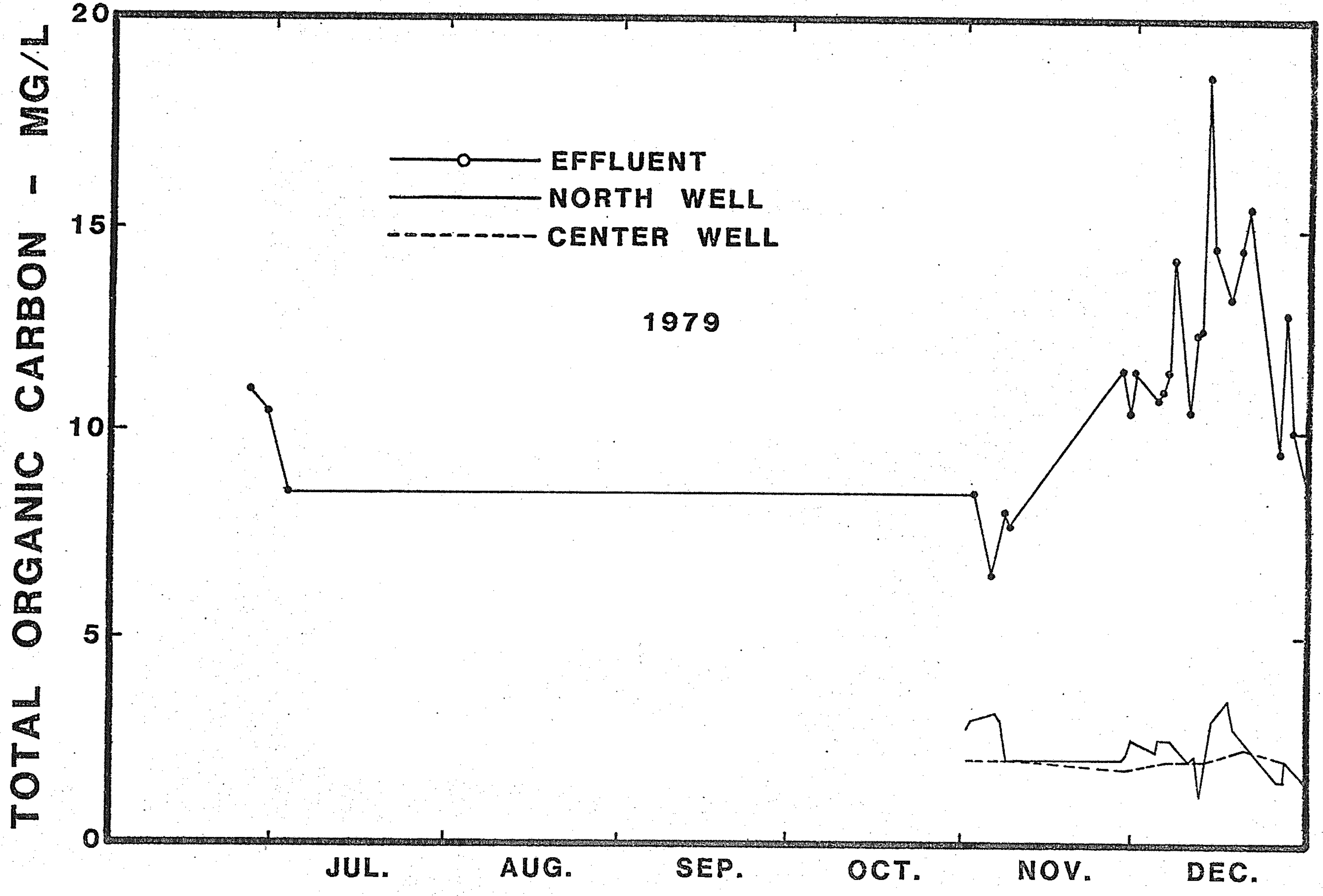


Figure 14. TOC concentrations in secondary effluent and renovated water from NW and CW.

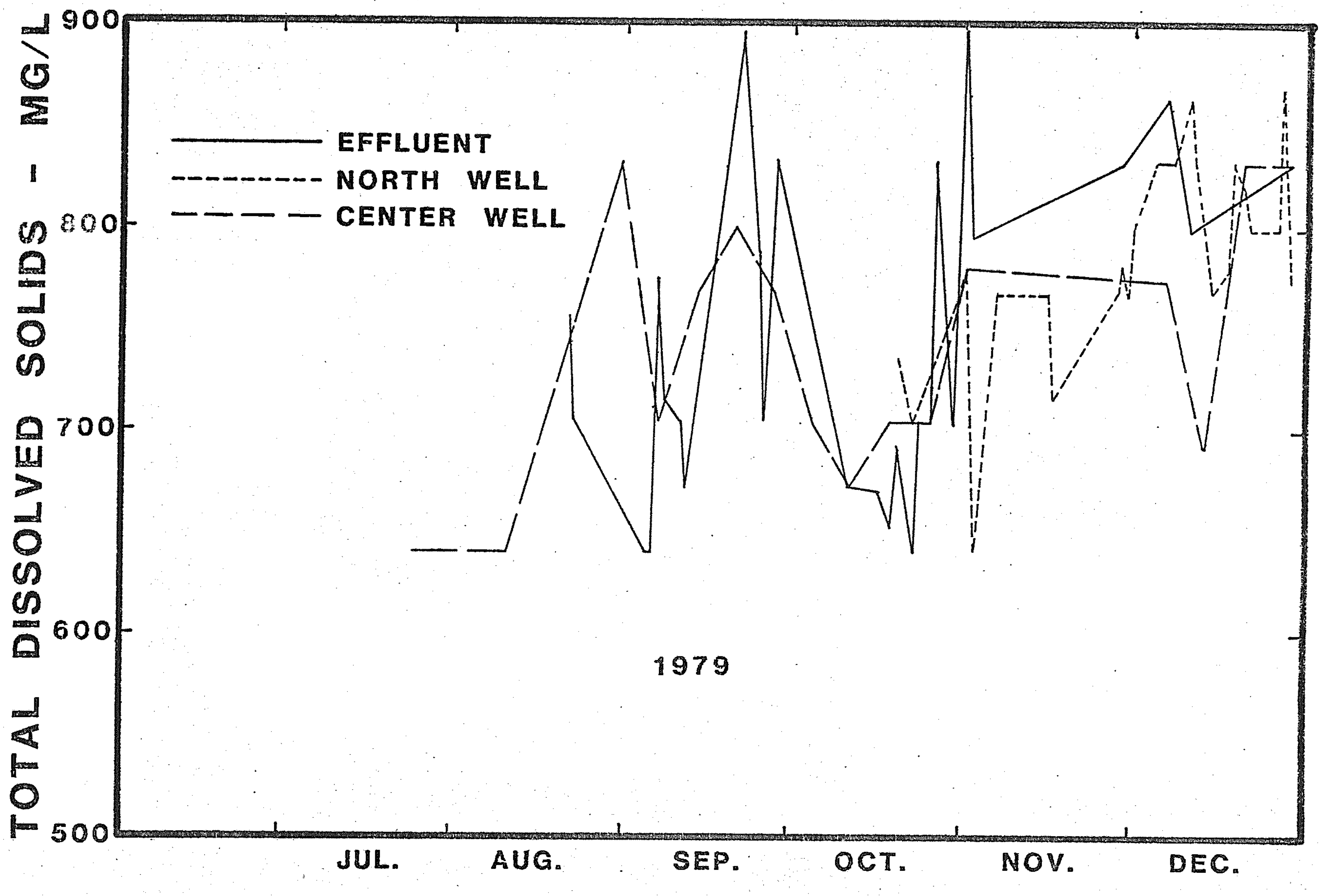


Figure 15: TDS concentrations in secondary effluent and renovated water from NW and CW.

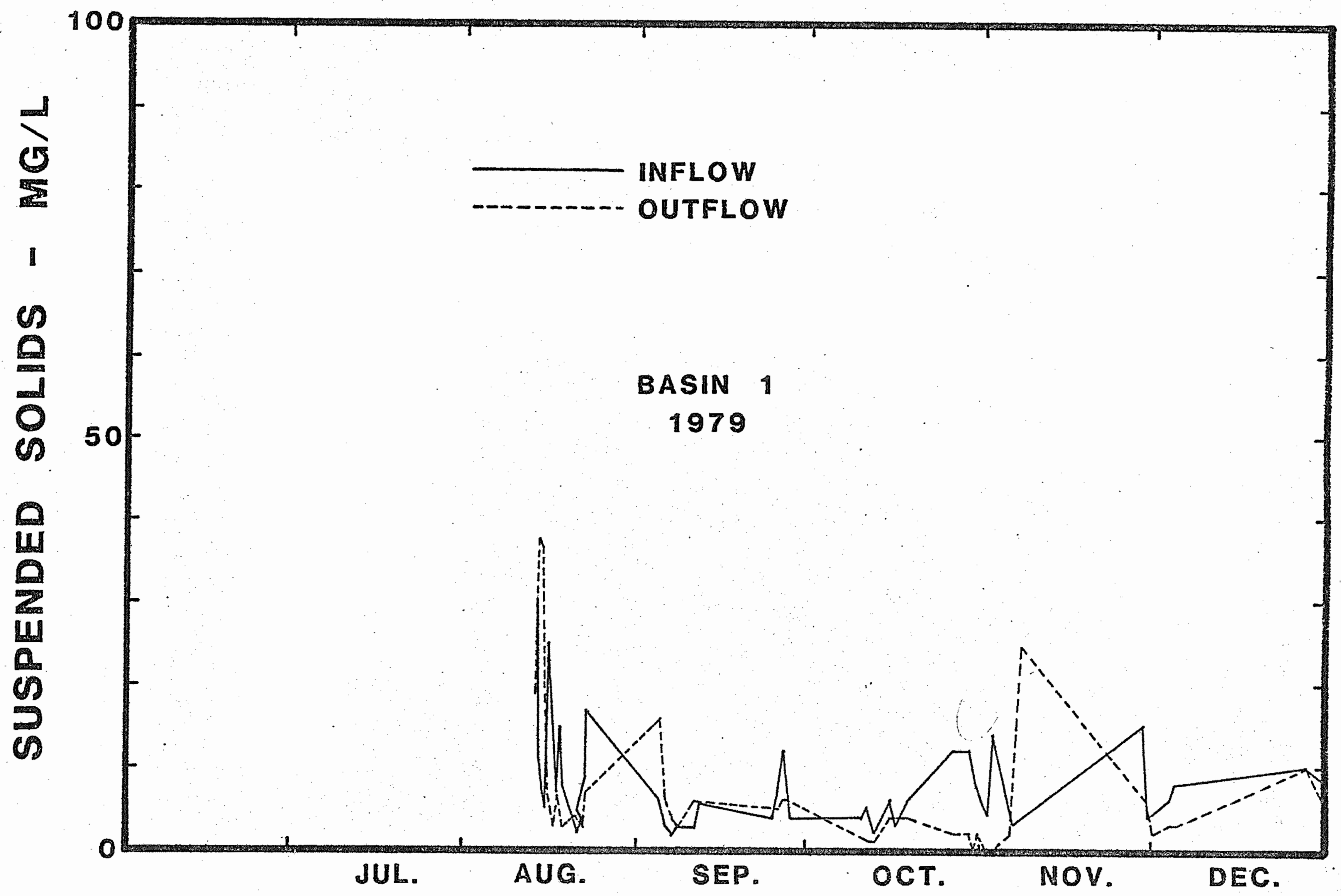


Figure 16. Suspended solids content of secondary effluent at inflow and outflow ends for basin 1.

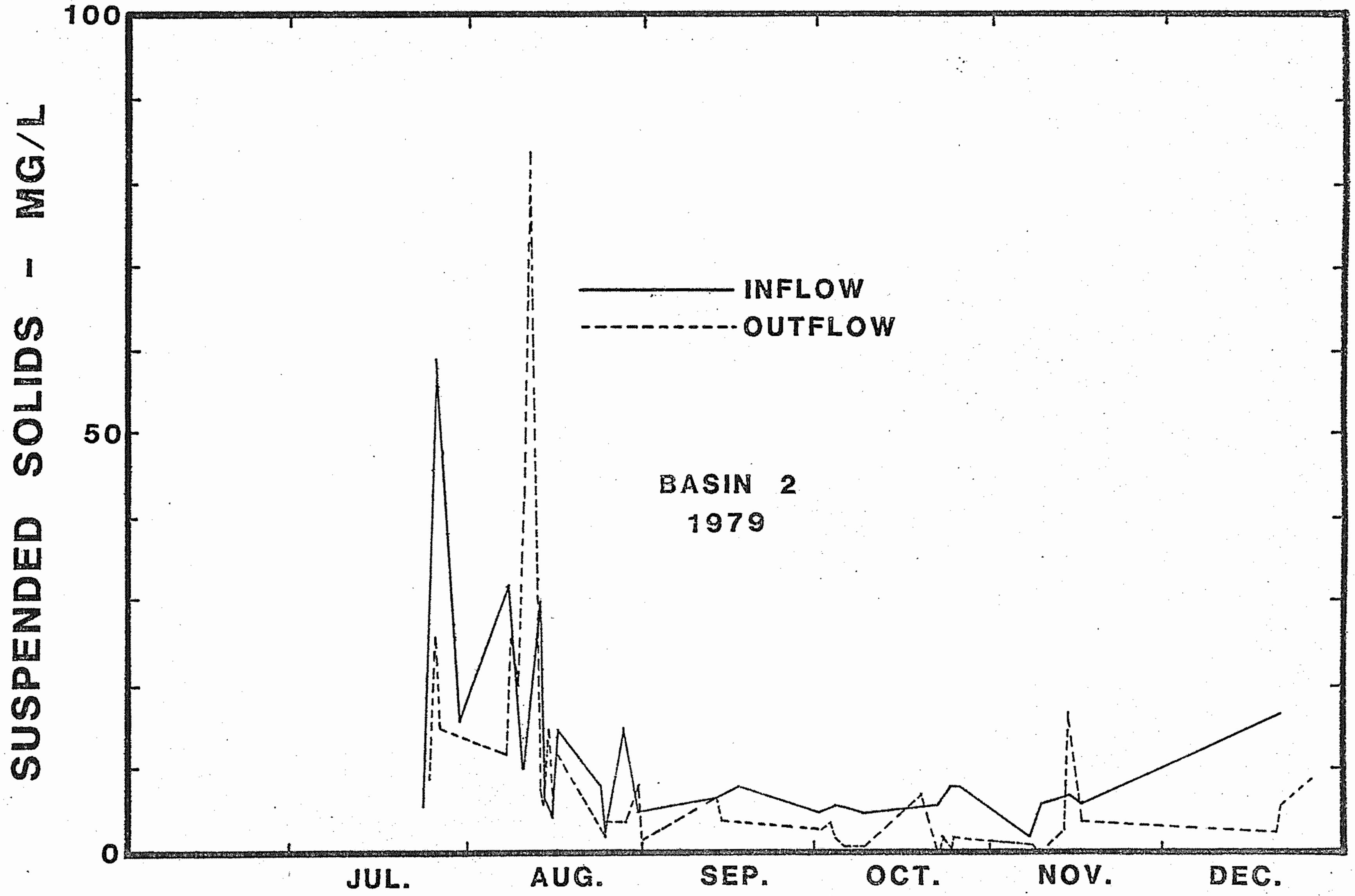


Figure 17. Suspended solids content of secondary effluent at inflow and outflow ends for basin 2.

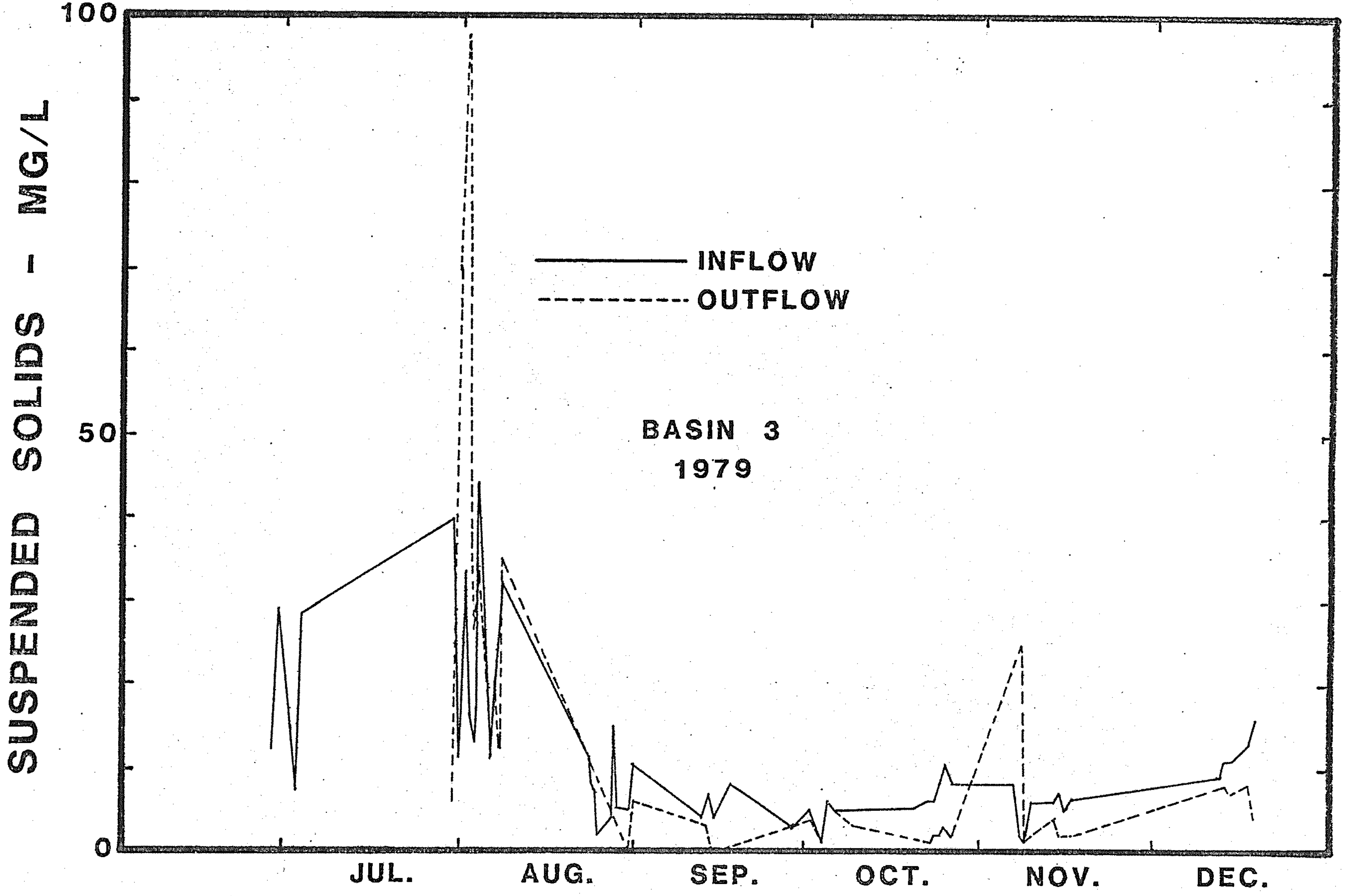


Figure 18. Suspended solids content of secondary effluent at inflow and outflow ends for basin 3.

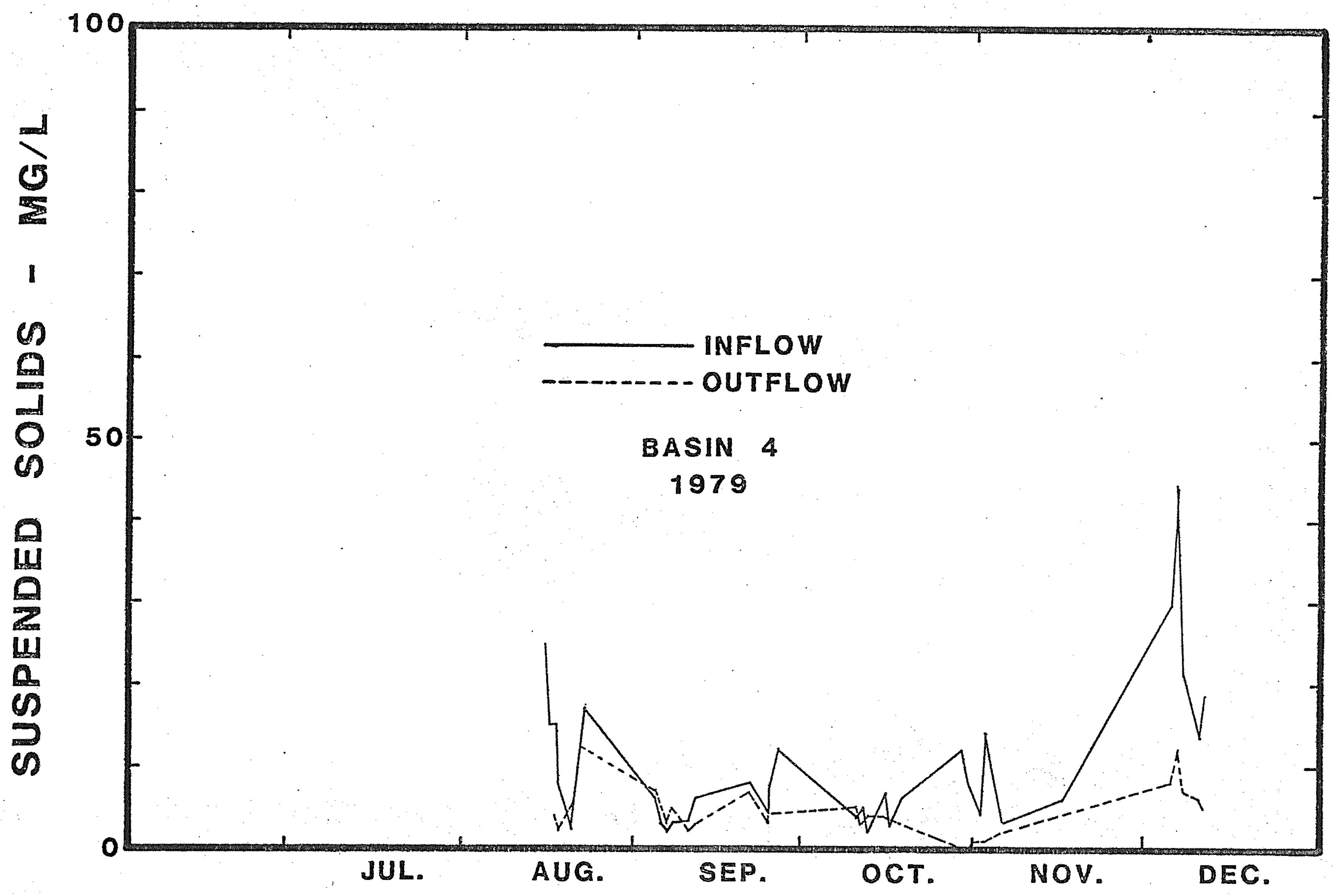


Figure 19. Suspended solids content of secondary effluent at inflow and outflow ends for basin 4.

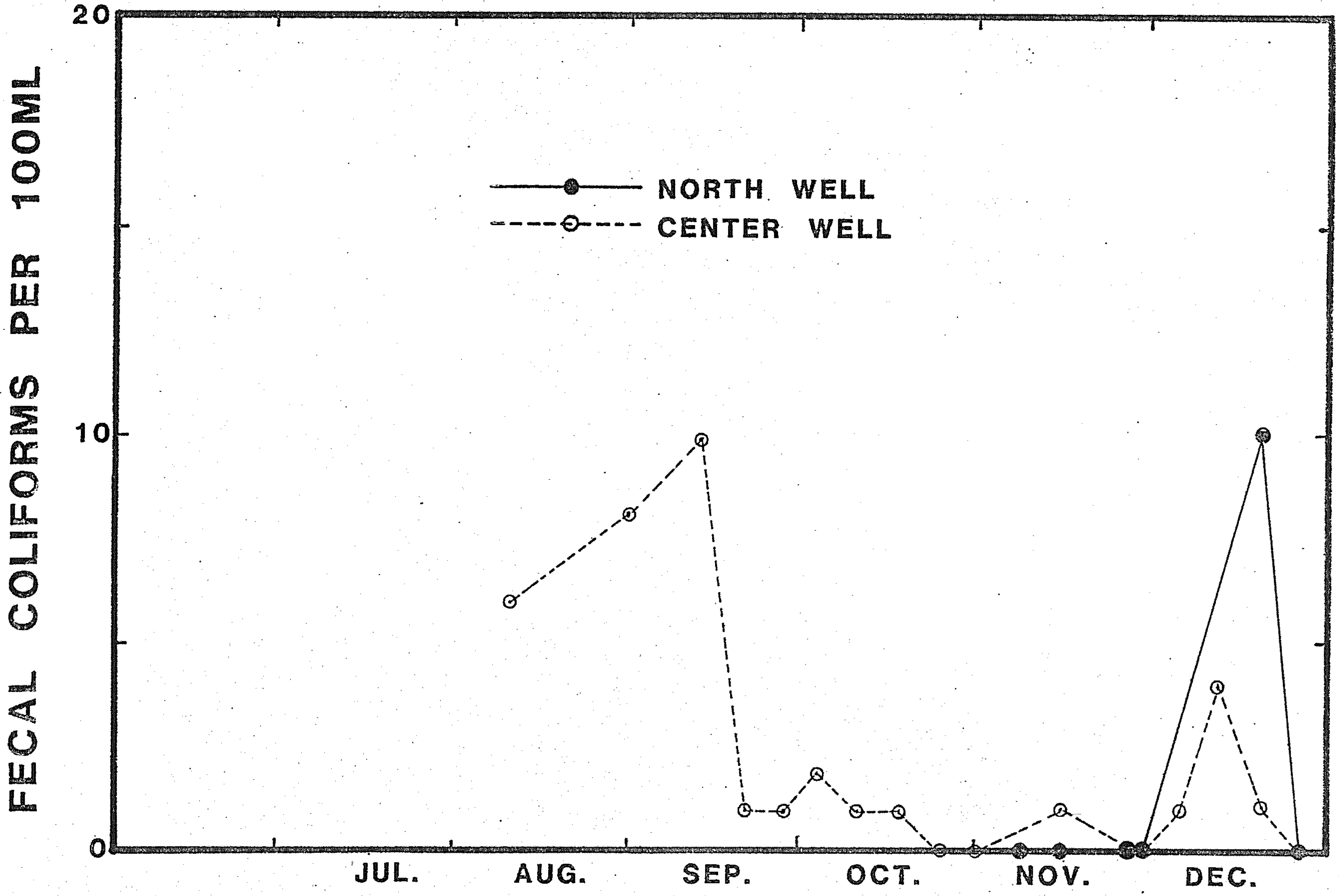


Figure 20. Fecal coliform concentrations in renovated water from NW and CW.

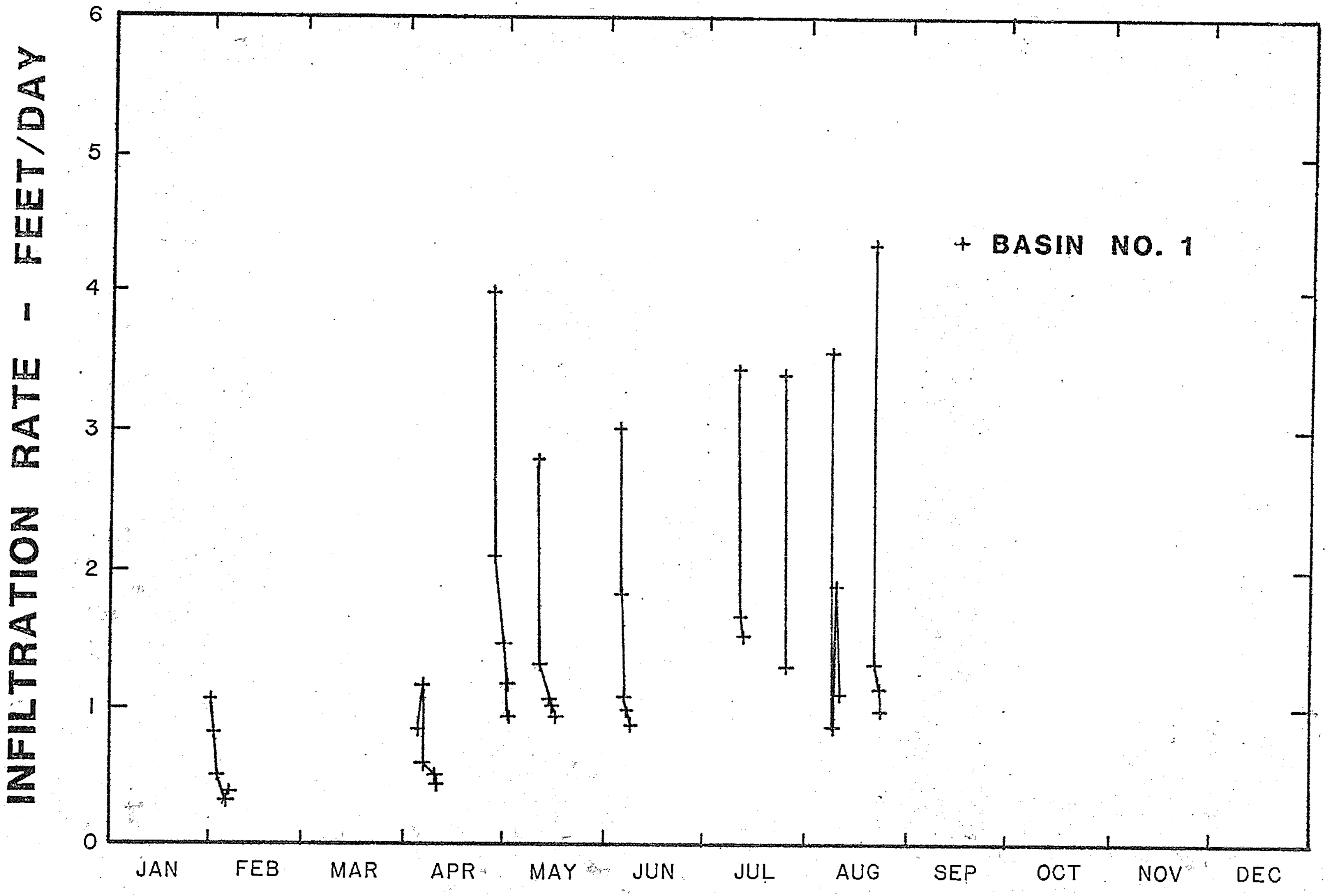


Figure 21. Infiltration rates for basin 1 at Mesa.

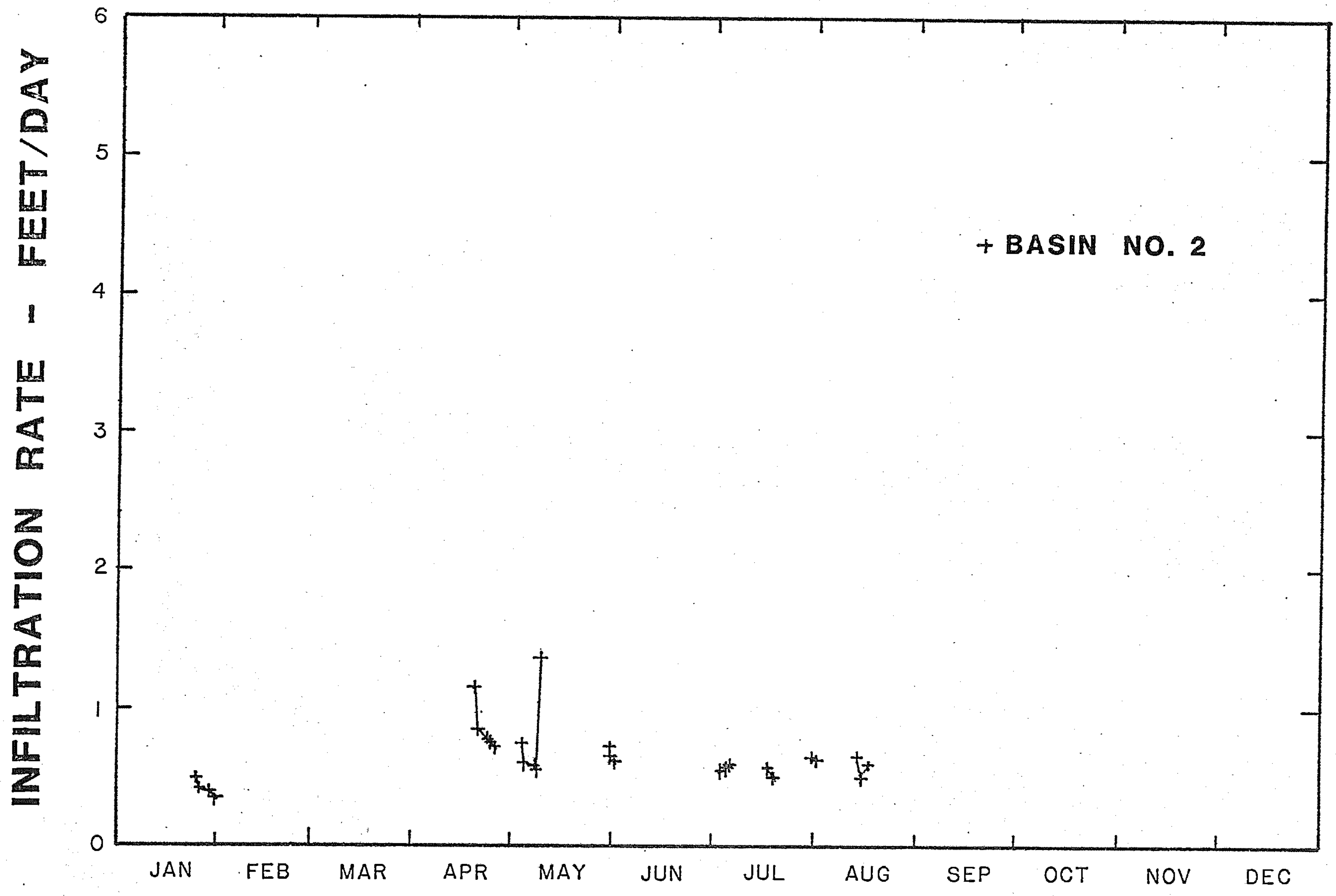


Figure 22. Infiltration rates for basin 2 at Mesa.

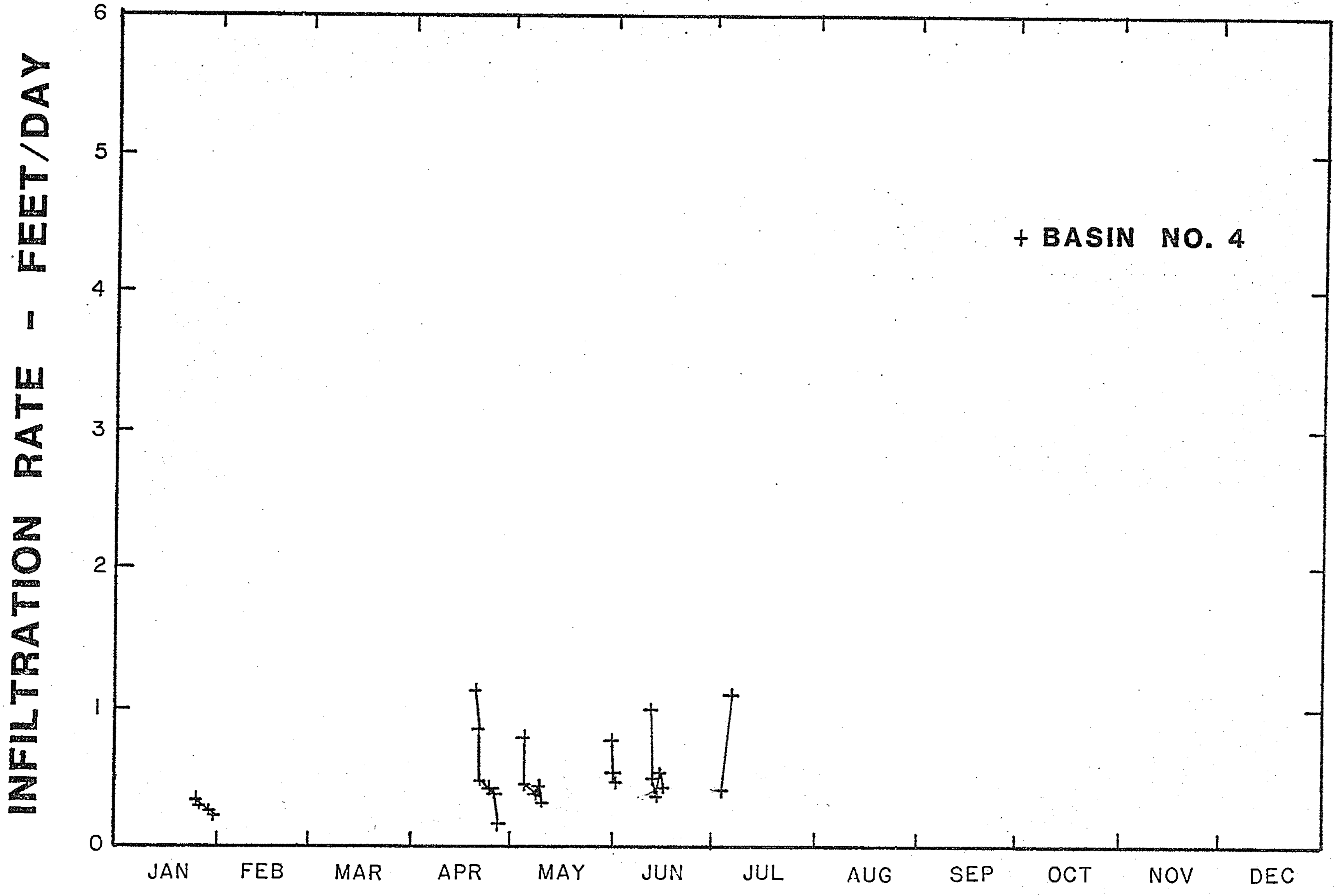
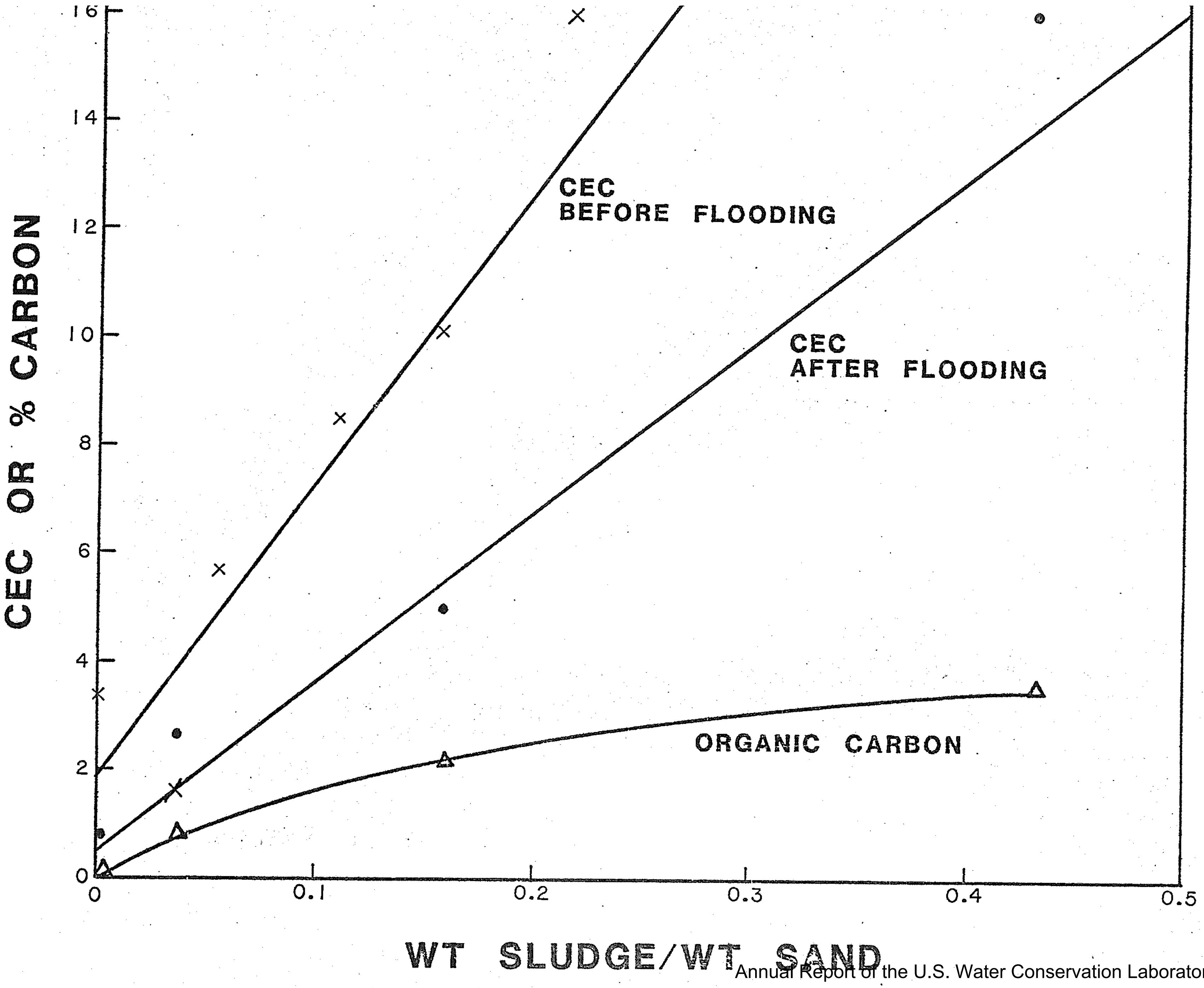


Figure 23. Infiltration rates for basin 4 at Mesa.



gure 24. Cation exchange capacity (CEC) in meq/100 g and percent organic carbon for different ratios of sludge to sand.

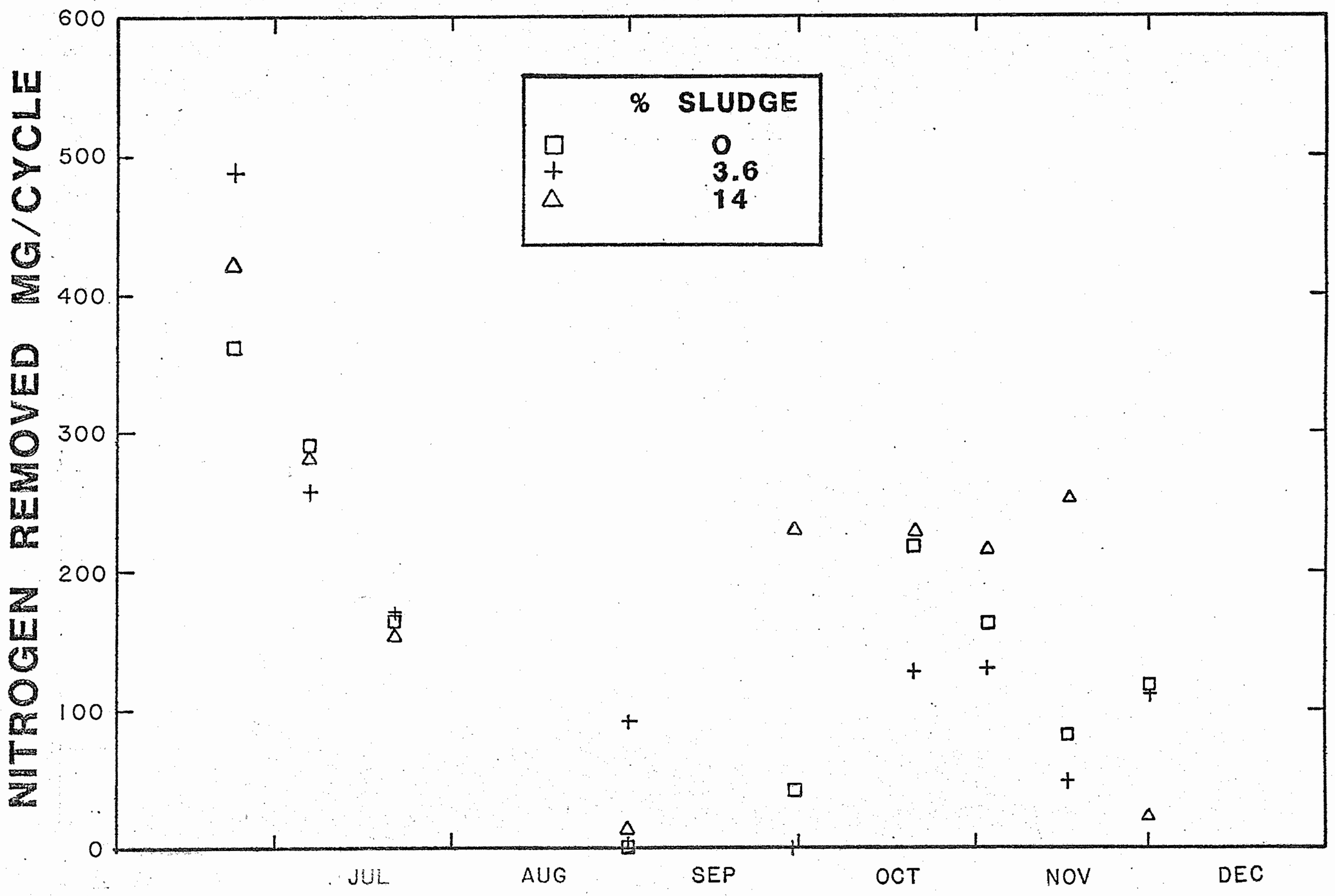


Figure 25. Nitrogen removal for different rates of sludge additions.

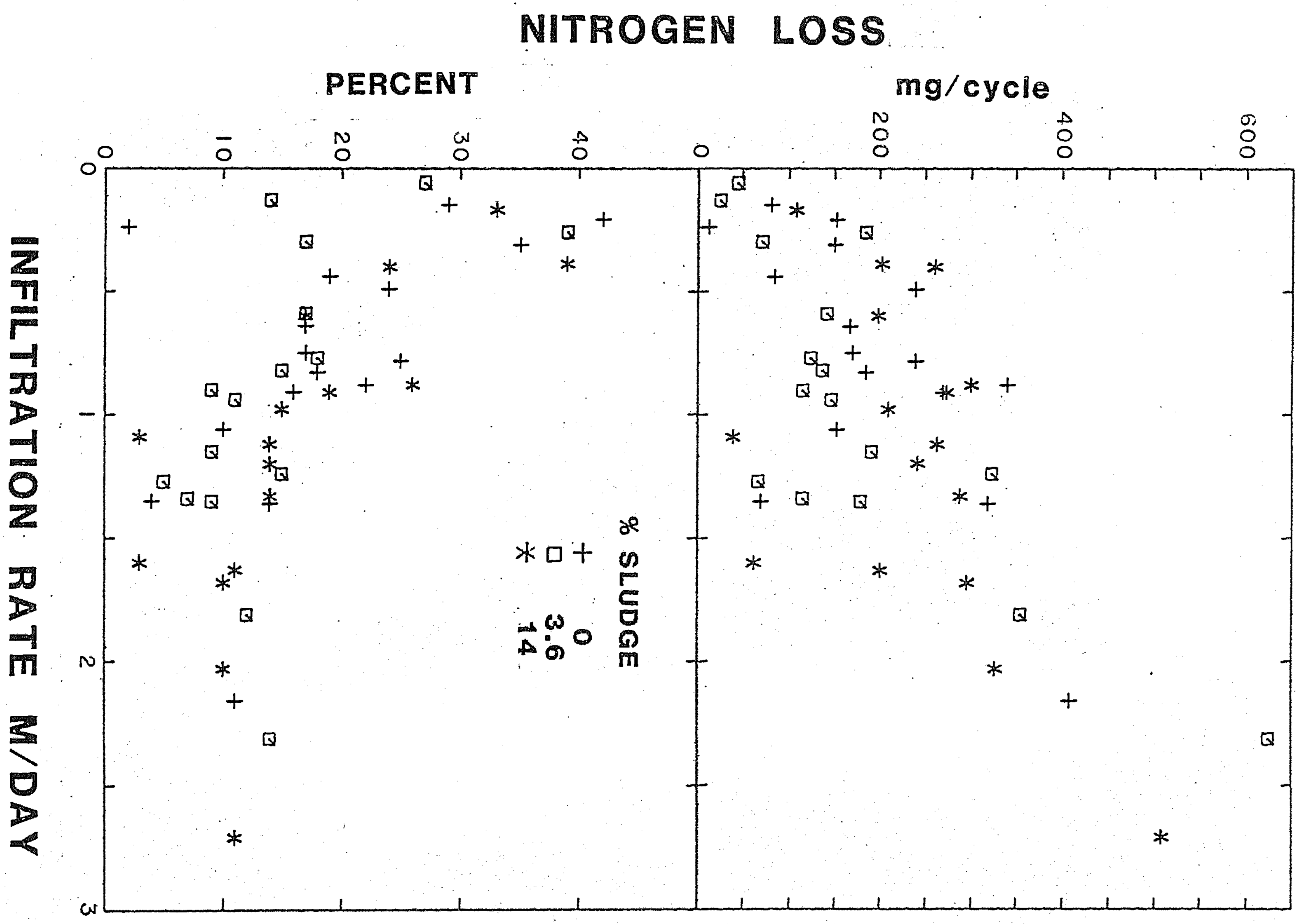


Figure 26. Nitrogen loss in mg/cycle and percent as functions of infiltration rate.

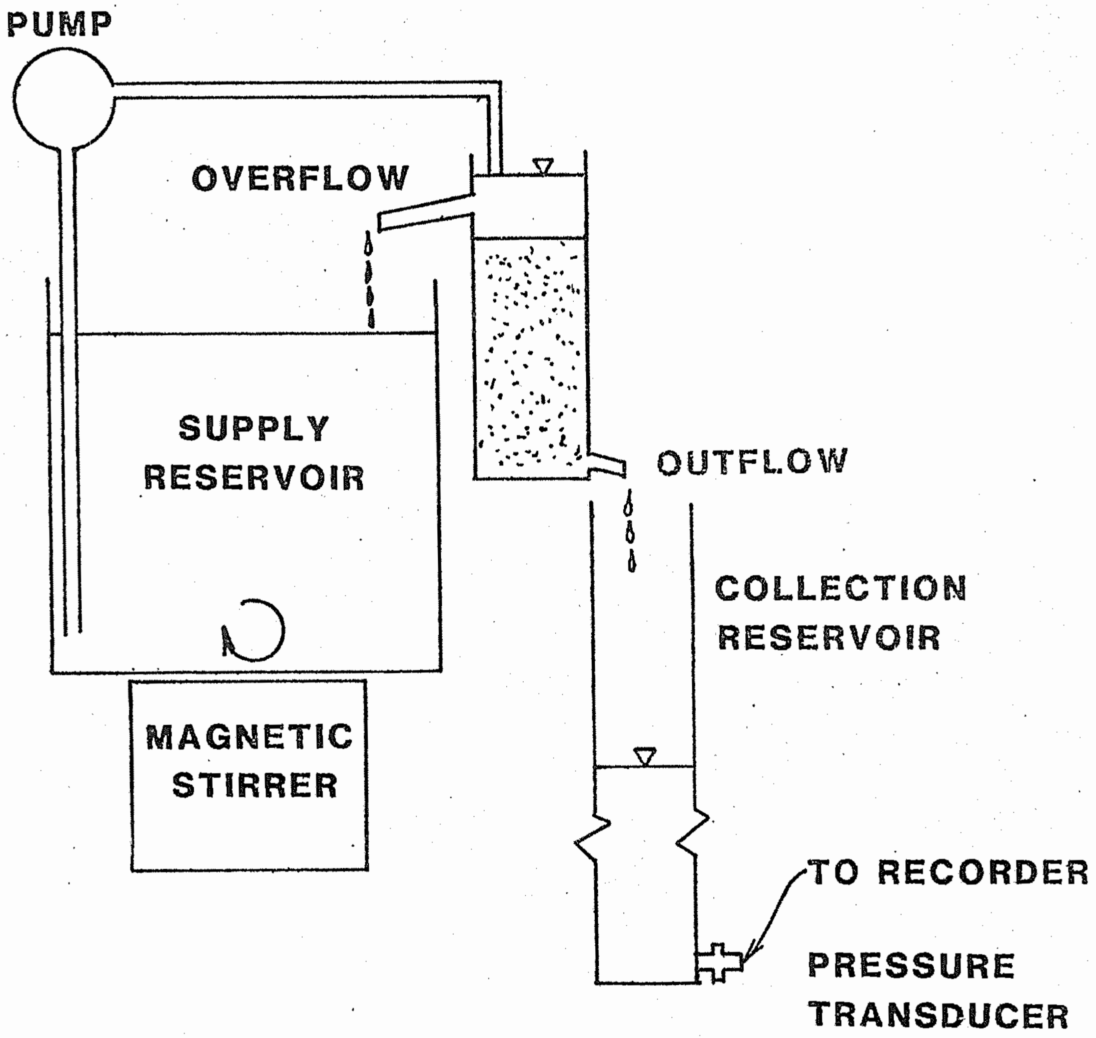


Figure 27. Test apparatus for α determination.

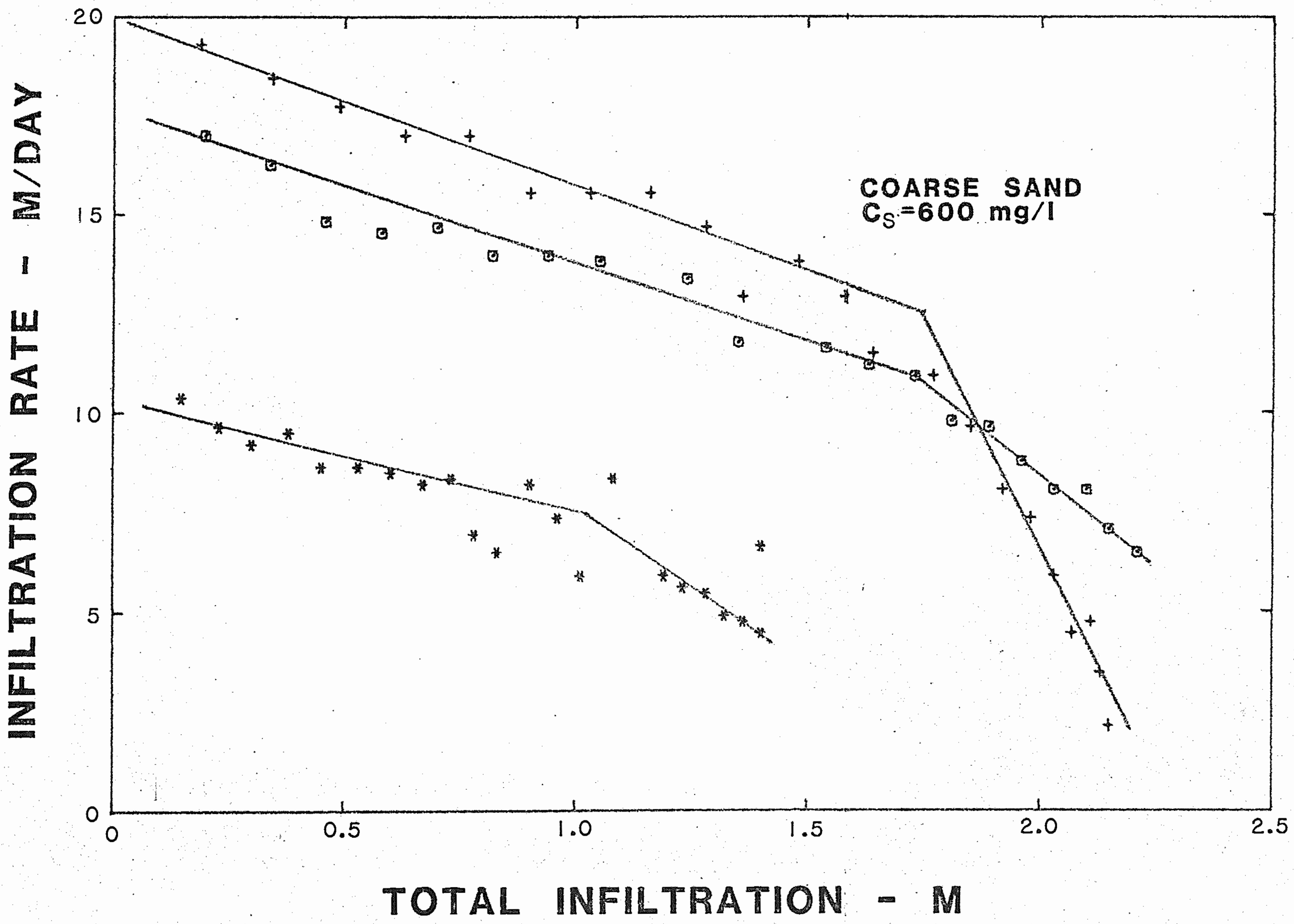


Figure 28. Total infiltration in relation to infiltration rate for coarse sand and C_s = 600 mg/ℓ.

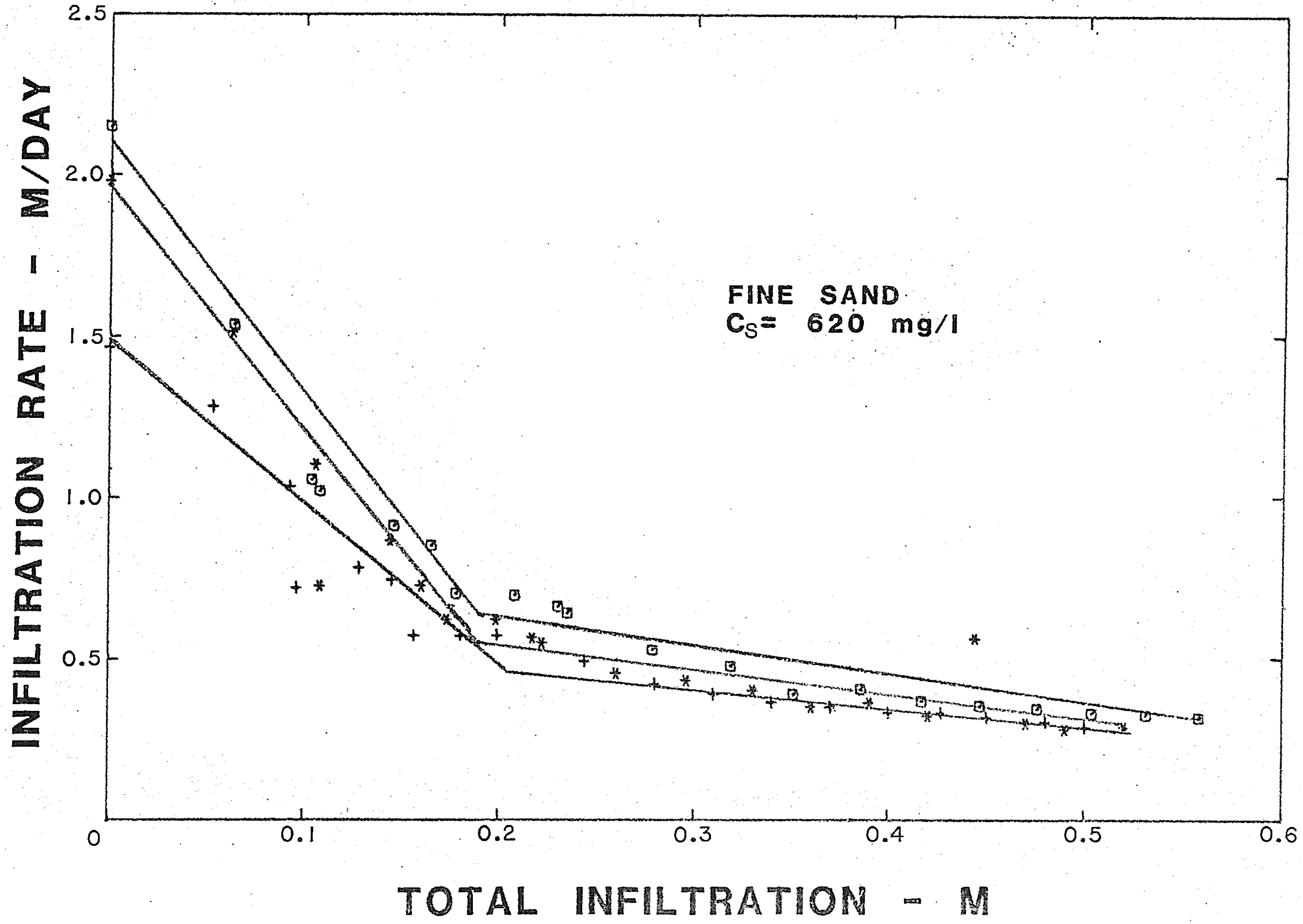


Figure 29. Total infiltration in relation to infiltration rate for fine sand and C_s = 620 mg/ℓ.

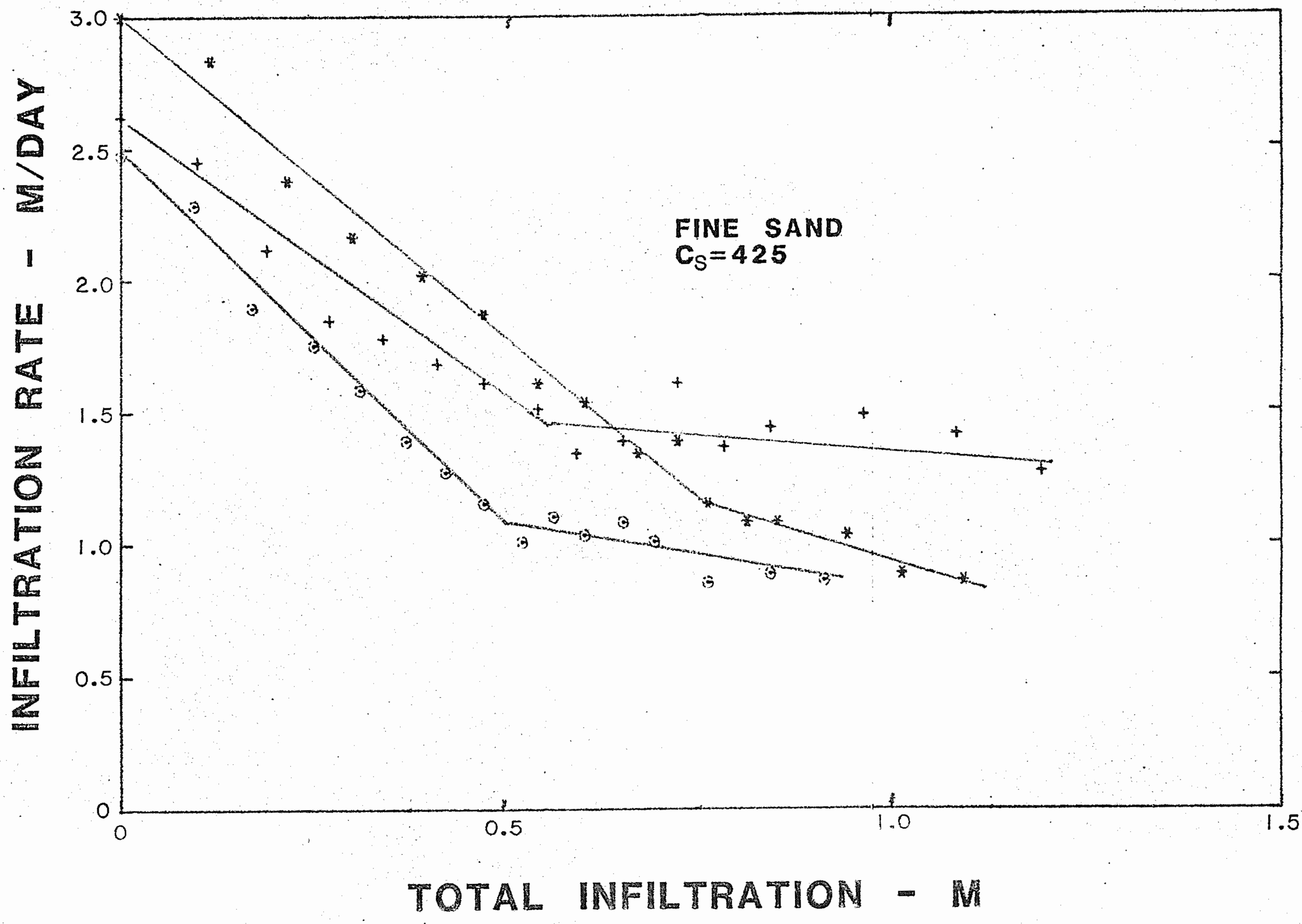


Figure 30. Total infiltration in relation to infiltration rate for fine sand and C_s = 425 mg/ℓ.

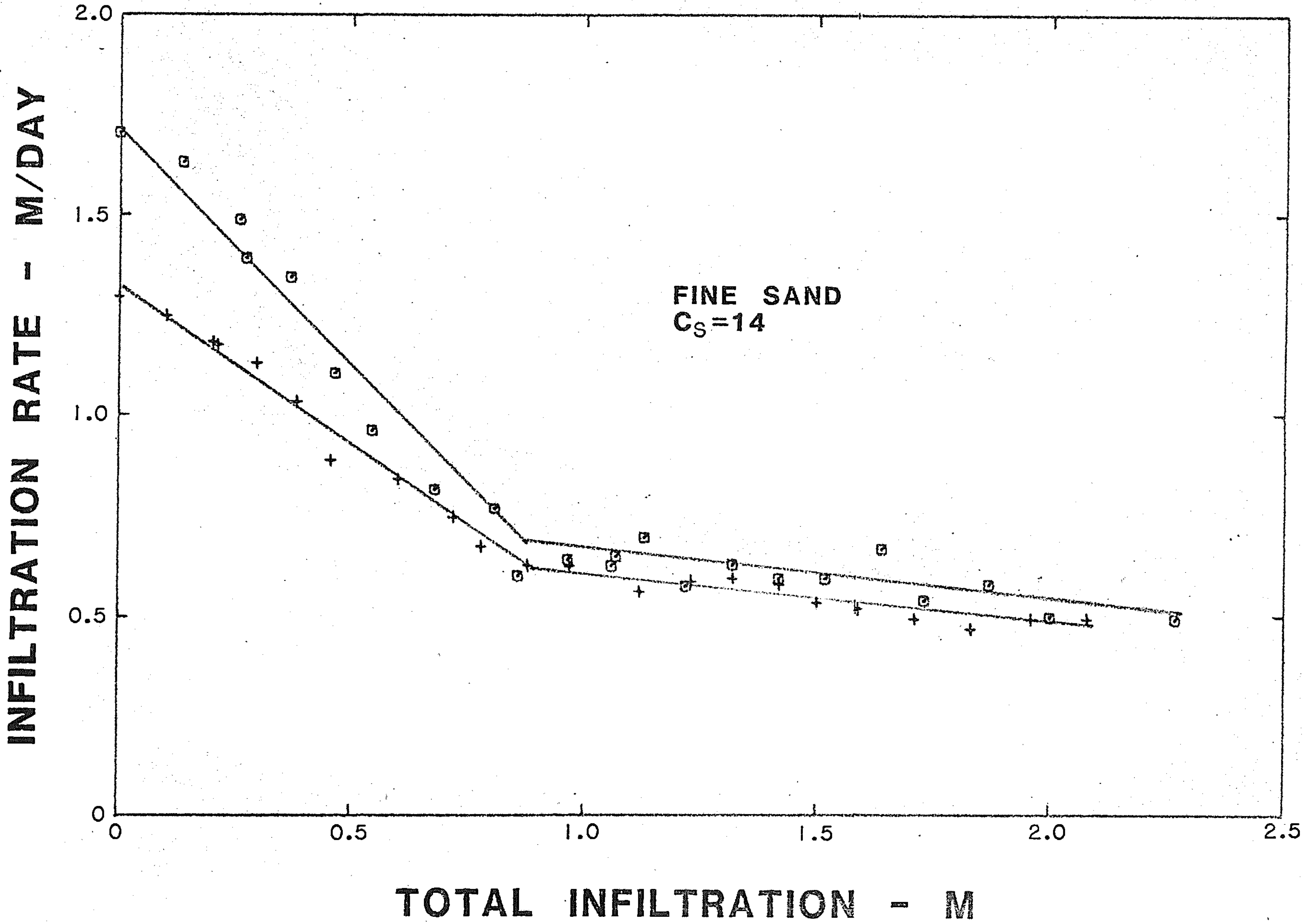


Figure 31. Total infiltration in relation to infiltration rate for fine sand and C_s = 14 mg/ℓ.

TITLE: COLUMN STUDIES OF THE CHEMICAL, PHYSICAL AND BIOLOGICAL PROCESSES OF WASTEWATER RENOVATION BY PERCOLATION THROUGH THE SOIL

NRP: 20790 CRIS WORK UNIT: 5510-20790-004

INTRODUCTION:

Virus research during 1979 was focused on the effect of different salts on virus adsorption, the adsorption of different viruses and coliphages applied simultaneously in the sewage water and the effect of prolonged leaching with deionized water on virus and coliphage desorption. Cooperative projects with Baylor College of Medicine involved completion of studies on virus survival under field conditons, adsorption of viruses by columns packed with several different soils and studies on endotoxin movement through soil columns.

Nitrogen studies involved using short dry periods (2-3 hours) at intervals during long flooding periods (9 days) in an effort to stimulate nitrification and subsequent denitrification during the long flooding periods. Cooperative projects were initiated with Rice University and Stanford University to identify trace organics in the sewage effluent and in renovated water from the soil columns.

PROCEDURE:

Virus Studies

Salt studies: One loamy sand column that had been used in several previous experiments on virus movement was conditioned by flooding with tap water for 3 days and drying for 2 days before experiments on virus adsorption from salt solutions began. The column was then flooded with a series of salt solutions containing 2 to 8 x 10^5 PFU/ml of poliovirus. The salt concentrations used and the order in which the column was flooded with the different solutions is shown in Table 1. The column was flooded with tap water for three days between the application periods for each different salt. Each solution was applied for 2 days and samples were extracted from various column depths at 24, 48, and 52 hours after flooding. The samples were frozen and shipped to Baylor College of Medicine for virus assays. Duplicate samples were also extracted for measurement of conductivity and Ca concentrations.

Virus and coliphage study: The soil column was flooded with secondary sewage effluent containing poliovirus, echovirus, F2 coliphage and MS2 coliphage at concentrations of about 10^3 PFU/ml. The columns were flooded for 3 days and samples were extracted at various depths on the second and third days of flooding. The columns were then flooded with deionized water for eight days and samples were extracted at various intervals.

Virus and coliform study: Column 5, which was packed with sand which had not been previously flooded with sewage water was flooded with secondary sewage effluent enriched with poliovirus. Free flowing samples collected through ports without using ceramic samplers were analyzed for fecal coliforms and duplicate samples were frozen for virus analysis. However a power failure caused the virus samples to melt and they were discarded. Samples for coliform counts were also collected from other columns that had been flooded with sewage at various times.

N removal study: Four soil columns were flooded with secondary sewage effluent on a schedule of 9 days flooding and 5 days drying. During three flooding periods the columns were drained for short times during the 6th, 7th and 8th days of flooding cycle. The average length of the dry periods was 2.7 hours. Two columns were then returned to regular 9-day flooding and 5-day drying cycles to prepare them for experiments with sludge additions.

Cooperative studies

Virus survival - Baylor: The soil samples collected last year were assayed and the data has been processed. One paper is in preparation.

Ceramic samplers - Baylor: Samplers constructed here and at Baylor were tested to determine if viruses move through the ceramic when water samples were extracted from soil columns. A publication has been accepted and the abstract is presented in the results section.

Endotoxin - Baylor: Soil columns here and at Baylor were flooded with secondary sewage effluent and samples from various depths were analyzed for bacterial endotoxins. Deionized water was applied to determine if endotoxins could be desorbed from soil columns. One publication has been accepted and is summarized in the results section.

Virus adsorption by different soils - Baylor: Soils which have been characterized with respect to texture, CEC, surface area and several other parameters were packed in 87-cm long soil columns at Baylor. The columns were flooded with secondary sewage effluent containing poliovirus and echovirus at different times and samples were extracted at various depths. The four soils used were Flushing Meadows loamy sand, Rubicon sand, Pomello sand and Anthony sandy loam.

Trace organics - Stanford: Secondary sewage effluent was applied to 3 soil columns and tap water was applied to another column on a 9-day flooding and 5-day drying schedule. All of the columns had been used in previous experiments with secondary sewage effluent. The sewage effluent and column outflow were sampled periodically with glass bottles for analysis of organic constituents by 3 gas chromatographic (GC) procedures. In addition 60 mℓ samples were collected for trihalomethane analysis.

The three gas chromatographic procedures used were: volatile organic analysis (VOA), closed-loop stripping analysis (CLSA), and solvent extract analysis (SEA). In essence, the VOA evaluated concentrations of the trihalomethanes and several other one- and two-carbon halogenated organics. CLSA allowed evaluation for many heavier chlorinated and unchlorinated organics with low and medium polarity such as chlorinated benzenes, naphthalenes, ketones, alcohols, and unsaturated hydrocarbons. The SEA technique permitted analysis for several compounds which cannot be removed from water by simple air-stripping such as pesticides, PCBs, and polynuclear aromatic hydrocarbons. Mass spectra for positive indentification were obained for the compounds separated by GC. Compounds were either quantified directly if standards were available, or if not available, then with respect to the concentration of internal standards as determined by peak area.

The tap water column was kept in operation for several months, and duplicate samples for CLSA were collected after 103 days. A publication has been prepared and its summarized in the results.

Trace organics - Rice University: Two soil columns in the insulated shelter were flooded with secondary effluent and the column outflow was sampled for trace organics. Fifty ℓ from each column were pumped through resin columns to concentrate trace organics which were analyzed with a gas chromatograph - mass spectrograph at Rice University. One column had been preconditioned by flooding with sewage for several days before sampling and one was flooded one day before sampling began.

RESULTS AND DISCUSSION:

Viruses suspended in deionized water moved farther down the column than viruses suspended in tap water (Fig. 1) Movement of viruses in sewage was intermediate between those two extremes. The increased adsorption of viruses in tap water probably is due to its salt content (≅ 300 ppm) and corresponding higher ionic strength. Although the salt concentration in the sewage water was more than twice that in tap water, the organic compounds in the sewage evidently retarded virus adsorption enough to make virus movement less with the sewage water than with the tap water. The increase in the adsorption rate from deionized water below 80 cm might have been caused by an increase in the salt content of the soil solution to more than 100 ppm. However, 95% of the viruses were adsorbed from deionized water in the upper part of the column before the water dissolved any appreciable amount of salt from the soil. Some viruses did move through the column outlet when deionized water was used while the maximum depth of penetration was 80- and 40 cm for the sewage water and tap water, respectively.

The effect of Na^+ and K^+ on virus adsorption was similar when chloride salt solutions of these cations containing viruses were applied to the soil columns (Fig. 2). As the concentration of the salt solutions increased virus adsorption increased also.

The divalent cations MG^{+2} and Ca^{+2} had a similar effect on virus adsorption and were more effective than monovalent cations when applied as chloride solutions (Fig. 3). This pattern of increased effectiveness with increases in salt concentration and valence suggested that virus adsorption might be proportional to the ionic strength of the solution. A plot of maximum virus penetration depth in the soil column vs. ionic strength provided further evidence that virus adsorption increased as the ionic strength increased (Fig. 4). The points for chloride salts were close to the line indicating that the different cations had no specific effect apart from their effect on the ionic strength of the solution. However points for KNO_3 fell well off the line, indicating that the NO_3 ion had a specific effect on virus adsorption. The comparison of virus adsorption from 1 mM solutions showed that 1 mM KNO_3 was as effective as 1 mM $MgCl_2$ in promoting virus adsorption (Fig. 5). The effect of different KNO_3 concentrations was similar in the range from 1- to 10 mM (Fig. 6). The KNO_3 solutions were more effective than NaCl and KCl solutions in displacing Ca^{+2} ions from the soil. Addition of the Ca^{+2} ions to the KNO_3 might have increased virus adsorption. However adsorption from KNO_3 solutions was also high at shallow depths (<10cm) where little Ca^{+2} was displaced. Work with other nitrate salts will be needed to be sure if this is a specific ion effect for NO_3^-.

Virus adsorption from sewage water seemed to follow the same pattern as adsorption from chloride solutions with the same ionic strength but virus adsorption from tap water was more than from chloride solutions of the same ionic strength (Fig. 4). The main difference in the tap water and the chloride solutions is the presence of SO_4 and HCO_3 and a combination of cations (rather than a single cation) in the tap water. More work will be needed to determine which of these factors increased virus adsorption from tap water. In the sewage water, the factors which promoted increased adsorption from tap water were evidently cancelled by a negative effect from organic compounds so that adsorption from sewage was similar to that from the chloride solutions.

The data from experiments with $AlCl_3$ and $CaSO_4$ were not included in the graph because viruses were not detected in many reservoir samples taken immediately after addition of viruses to the solutions. The

$AlCl_3$ experiments were repeated and every reservoir sample except one showed 0 virus concentration in the 10 mM solutions. The virus concentrations in the reservoirs of 1 mM $AlCl_3$ ranged from 0 to 10^5 PFU/mℓ. $LaCl_3$ solutions were tried with generally similar results. The $CaSO_4$ reservoir samples contained viruses but the results were quite erratic. Although the $AlCl_3$ appeared to be dissolved it might have formed colloidal flocs which adsorbed viruses. This may be why $AlCl_3$ addition to water increases the effectiveness of filters used for virus concentration.

Virus and Coliphage study:

The attempt to study movement of two different virus simultaniously was unsuccessful due to problems with the virus assay. The poliovirus was detected but no plaques were produced for the echovirus. Adsorption patterns for the two coliphages, f_2 and MS_2 patterns, were similar to those for poliovirus except that phages were concentrated even closer to the soil surface (Table 2). This is not in agreement with some data from the Baylor Lab showing more movement of coliphage. More work may be needed to clarify this point. Leaching of phages with deionized water also seemed similar to leaching of poliovirus (Table3).

When the column was leached with deionized water for eight days following the addition of viruses in sewage, a few viruses were detected in samples on the eighth day (Fig. 7). However, very few viruses moved to the 80 cm depth and none were detected at the bottom of the column. This shows that prolonged flooding with deionized water to simulate rainfall does not cause much virus movement.

Virus And Coliform Study:

This study was initiated to study simultaneously the movement of poliovirus and coliforms through the same column. However, virus samples were lost when a refrigerator defrosted and more samples must be taken in the future. The coliform counts showed that column 5, which had not been flooded previously with sewage, removed all of the coliforms in the top 40 cm (Table 4). However, after several days of flooding, the coliforms moved through the entire 250-cm column. Apparently coliforms were initially adsorbed and finally broke through when the adsorption capacity was saturated.

One problem with coliforms counts has not been explained. The coliform counts in plastic jugs of secondary effluent did not decline much during overnight storage. However, the counts in the glass reservoirs and in the column head dropped by 1 or 2 logs. The coliform counts in the 2-cm samples also were low, but counts down the column gradually increased until they were almost as high as counts in the plastic effluent jugs at the 20- to 40-cm level (Table 4). The counts then declined again until they were 0 or very low at the column outlet.

Evidently something in the jug and the column head damaged coliform bacteria so that the counts were low in the samples in the glass carboy and near the soil surface. The damage must have been reversed as the coliforms moved through the soil so that counts increased at the 40-cm level and then declined as would be expected during travel through a long soil column. We thought that the small amount of antibiotic in the stock virus solution might cause the damage but the trend continued when the virus culture was omitted. Also, columns 1, 4, and 7 showed the same trend. Columns 1 and 4 had not received viruses recently and no virus had been applied to column 7. Samples of sewage in amber and clear bottles showed that light only caused a slight reduction in coliform counts. Possibly some kinds of toxic compounds build up un the glass carboys, plastic lines, and in the column head. Since using an acid-washed glass carboy did not solve the problem, the toxic compounds must not be limited to the glass carboy. Also its possible that such toxic compounds are adsorbed near the soil surface so that normal coliform counts are detected below the 20- to 40-cm depth. More work will be needed to clarify this point.

N removal study - short dry period:

Using 3 short dry periods of about 3 hours each allowed 0.6 to 1.1 liter of water to drain from the columns and a corresponding amount of air to enter by mass flow (Table 6). Since oxygen also entered the columns by diffusion, a considerable amount of oxygen was available for denitrification. The nitrogen removal rates during the 3 cycles with short dry periods (01/18 to 03/01) increased slightly above the usual average of about 30% (Table 6). Then the experiment was terminated and the columns were dry for about 11 weeks. Regular 9-day flooded and 5-day dry cycles were begun on 05/31 to prepare the columns for the experiments with sludge. The nitrogen removal was excellent for the first 3 cycles. This probably represents a carryover effect from the short dry experiment. Nitrogen stored by the column was probably depleted during that experiment and replacement of that nitrogen increased N removal during subsequent cycles. The short dry period method probably would have been effective if it had been continued for a long enough time for the columns to reach equilibrium. However, I have decided that it would be difficult to implement this idea in a practical field system.

Phosphate studies:

Phosphate concentrations in the column outflow were higher than those in the incoming sewage water when flooding was resumed in 1978, after a long dry-up. During 1979, the phosphate concentrations in outflow from column 8 continued to decline until it was below the P concentration in the sewage (Fig. 8). Apparently a long flooding period is required for all available phosphate to be leached out after a very long dry period during 1976 and 1977. A reduction in the phosphate content of the sewage water with time probably lengthened the equilibration time. Dry periods of 2 to 3 months during 1979 did not cause additional release of phosphate, indicating that very long dry periods are required to increase its availability to leaching.

Cooperative Studies

Virus Survival-Baylor: A manuscript entitled "Survival of enteroviruses in rapid infiltration basins during the land application of wastewater," by C. J. Hurst, C. P. Gerba, J. C. Lance and R. C. Rice has been prepared and a summary is presented here.

The finding in the present study shows that virus concentrations in the upper surface of the soil profile were approximately 1 $\log_{10}$ higher than those found between the 2.5 and 25 cm (Table 7) levels closely corresponds with the earlier data concerning the removal of enteroviruses from wastewater applied to laboratory columns of the same soil. We found that 1 $\log_{10}$ of virus was removed by passage of effluent through the first few centimters of the soil column, with removal being less at greater depths in the column. Thus, studies with long soil columns may provide good model systems for virus removal under field conditions.

Virus did not persist for extended periods of time in the soil. Virus buried in the small open tubes could be detected on day 19 and appeared to survive a second flooding period. The titer of virus found on day 19, however, was much lower than those found on day 1. Indigenous virus in the basin soil could not be detected in the fifth day of drying. Seeded poliovirus in the open soil of the small basin was detectable on day 4 but not on day 8. The average percent reductions in virus titer (per day, between sampling dates) and the rates of reduction in virus titer were similar for both poliovirus 1 and echovirus 1 in the buried pipe section (Table 8). The percent reductions and rates of reduction in virus titer for poliovirus 1 and indigenous virus in open soil were likewise similar and were nearly identical to the reductions in virus titer which occurred for the seeded virus in pipe sections. The laboratory-derived value for rate of virus titer reduction at a constant 15% moisture and at the temperature of the fall field study (average 25 C) would be 0.235 log reduction in virus titer per day (data not shown). This laboratory-study-derived value is approximately one-half of the actual field study inactivation rate, indicating that survival of viruses under constant environmental conditions in the laboratory is not identical to survival under field conditions. This difference in virus survival was hardly unexpected, due to the constantly changing temperature and moisture level of soil in the field.

Conditions in the open soil, pipe sections, and open plastic tubes were thought to have been similar during this study with respect to environmental factors. The percentage reductions and rates of reduction in virus titers in the small plastic tubes were, however, less than those found in the pipe sections or open soil. The possible difference in conditions between virus buried in the different manners may have been the rate at which moisture passed from soil in the pipe sections and small tubes into the surrounding soil. The reason for this difference in rate of moisture transmission could be that a higher ratio of plastic surface-to-soil content volume existed for the contents of the small tubes in comparison to the pipe sections. Such a difference in ratio of plastic surface-to-soil content volume would be even greater between the tubes and open soil.

Drying of the soil has a major influence on the rate at which virus is inactivated. These results indicated that the observed differences in viral inactivation were due to differences in soil drying rates. It is important to note that poliovirus 1, echovirus 1, and the indigenous enterovirus population in the soil were all inactivated similarly with respect to drying.

Ceramic Samplers-Baylor:

A manuscript entitled "Evaluation of various soil water samplers for virological sampling," by De-Shin Wang, J. C. Lance, and C. P. Gerba, has been accepted by the Journal of Applied and Environmental Microbiology. The abstract is presented here.

Two commercially available soil water samplers and a ceramic sampler constructed in our laboratories were evaluated for their ability to recover viruses from both tap water and secondary sewage effluent. Our ceramic sampler consistently gave the best recoveries of viruses from water samples with recoveries ranging from 82- to 100% of controls. This compares to recoveries ranging from 0.03- to 79% for commercial samplers. Soil columns containing ceramic samplers at various depths provide a simple method for studying virus transport through sewage-contaminated soils.

Endotoxin - Baylor:

A manuscript entitled "Movement of endotoxin through soil columns," by S. M. Goyal, C. P. Gerba, and J. C. Lance, has been accepted by the Journal of Applied and Environmental Microbiology. The following is a brief summary of that paper.

Soil filtration of sewage water effectively removes most of the pollutants associated with sewage. Recently the presence of another class of pollutants called endotoxins has been demonstrated. These toxins are released when bacterial cells are ruptured. Thus these toxins may cause damage after the bacteria that produced them are dead. We used soil columns that have been used to study the movement of many other pollutants through the soil to study the adsorption and movement of endotoxins. We found that at least 90% of the endotoxins present in sewage water were adsorbed by the soil columns. However, part of the endotoxin could be desorbed and move through the soil when the columns were flooded with distilled water to simulate rainfall. Also, low concentrations of endotoxin were detected in well samples from groundwater below two land treatment systems at other locations (Lubbock, TX and Fort Devins, MA). Since the minimum concentration of endotoxin that is a health threat to humans has not been firmly established, more work on movement of endotoxins to groundwater is needed.

Virus Adsoption by Different Soils - Baylor:

Soil column experiments concerning virus movement through soil into groundwater have been conducted previously in our laboratories using a loamy sand from the Flushing Meadows groundwater recharge basin near Phoenix, Arizona. In those studies, it was shown that most of the viruses were removed in the top few centimeters of the soil. The purpose of this study was to evaluate the migration of viruses through different types of soil as wastewater percolated through soil columns. The chemical and physical characteristics of these soils are presented in Table 9.

Poliovirus 1 (strain LSc) and echovirus 1 (V239; isolated from groundwater by the Baylor laboratory) were added to secondary sewage effluent to give an average concentration of 10^4 to 5 x 10^4, plaque-forming units per mℓ. Seeded sewage effluent was percolated through soil columns continuously for 4 days at a constant flow rate during each experiment. An approximate 3-mℓ amount of water sample was extracted daily from ceramic samplers at depths of 2, 7, 17, 27, 37, 47, and 67 cm, and from the outlet line at 87 cm for virus assay. Data were averaged for samples taken on 4 flooding days.

Of the four soils studied, the Anthony sandy loam removed 99% of the seeded polio 1 within the first 7 cm of the soil column at an infiltration rate of 28 cm/day (Fig. 9). Flushing Meadows loamy sand removed 99% of the seeded polio 1 when wastewater percolated through 27 cm of the soil column at an infiltration rate of 76 cm/day. Removal of polio 1 by Pomello sand having a flow rate of 208 cm/day was less efficient; 1% of the seeded virus moved through the outlet of the column at the 87-cm depth. Rubicon sand with an infiltration rate of 300 cm/day gave the poorest removal of polio 1 -- 13% of the virus remained in the water sample at the outlet of the column.

In general, the movment of echo 1 through the soil columns at the same infiltration rates was similar to that of polio 1 (Figs. 9 and 10). The removal of echo 1 in Anthony sandy loam and Rubicon sand was different from polio 1 only in the top 2 cm. Polio 1 was removed more efficiently than echo 2 in Flushing Meadows loamy sand and Pomello sand above the 47- and 27-cm depths, respectively, but the concentrations of the viruses at lower depths were similar. When the percent of viruses remaining at the column outlet were plotted vs. flow rate, it appeared that differences in adsorption by different soils were due to differences in flow rate (Fig. 11).

In summary, the movement of these two viruses into groundwater differed with different types of soil. It appeared that a depth of 67 cm was sufficient for effective removal of the two viruses from Anthony sandy loam, Flushing Meadows loamy sand, and Pomello sand, but not from Rubicon sand. Groundwater contamination might occur with Rubicon sand if the water table is within 87 cm of the soil surface. This study suggests that soil permeability may be the most important factor in determining the potential for virus movement through a soil.

Trace Organics - Stanford:

A manuscript entitled "Trace organic behavior in soil columns inudated with secondary sewage," by E. J. Bouwer, P. L. McCarty and J. C. Lance has been prepared and a summary is presented here. The results of VOA indicated the secondary sewage contained principally chloroform, 1, 1, 1-trichloroethane, and tetrachloroethylene in the range of 1-10 g/ℓ. These compounds also were present in the effluents of the soil columns apparently with complete breakthrough of chloroform. Concentrations of the other two organic compounds appeared to remain low relative to influent values, and the concentrations remained constant throughout the wetting and drying periods (Fig. 12). Hydraulic loading rate had no significant effect on percentage removals. The tap water had a higher chloroform concentration (~ 50μ g/ℓ) and contained more halogenated compounds (dichlorobromomethane, dibromochloromethane, bromoform, trichloroethylene, tetrachloroethylene) than the secondary sewage. The soil column effluent here contained only chloroform, 1, 1, 1-trichloroethane, and tetrachloroethylene at detectable concentrations. Chloroform measurements for the tap water column were similar to those inundated with secondary sewage. Concentrations of 1, 1, 1-trichloroethane and tetrachloroethylene in the tap water column effluent were below 2μ g/ℓ and indicated perhaps some leaching of these compounds had occurred.

The CLSA results (Table 10) for the column influents and effluents indicated the presence of up to 1μ g/ℓ of hydrocarbons, alcohols, ketones, chlorinated and unchlorinated aromatics, and several unknown compounds. Several compounds were detected in the secondary sewage, but not in the column effluents. Also, a few compounds found in the column effluents were not detected in the secondary sewage. Little change in the column effluent organic concentrations was observed with change in hydraulic loading rate or time throughout the wetting and drying periods. Column effluent concentrations were generally lower than column influent values. Interestingly, 2, 6-di-t-butyl-4-bromomethyl phenol was not attenuated in the soil columns. Few peaks appeared in CLSA chromatograms of the tap water, but the column effluent for the tap water system contained essentially the same peaks and concentrations as the other columns inundated with secondary sewage. After 103 days of percolation, tap water column effluent organic concentrations were nearly the same as observed during the initial 14-day period. This suggests prior storage and a significant amount of leaching of these compounds from the soil had occurred.

Compounds identified in the solvent extracts (Table 11) were mainly phthalates, anisoles, and a few pesticides. The concentrations of these compounds were quite low with several close to their detection limits. Several of the compounds were attenuated in the columns. Effluent concentrations were quite similar and uniform for all columns, and again showed little change with hydraulic loading rate or time. Some of the compounds showed no apparent removal. No SEA compounds were detected in the tap water, but again the effluent from the tap water column was similar to that from the other three columns. This is further evidence that leaching of previously sorbed compounds was taking place.

This study was performed to give a general indication of the behavior of trace organics in soil column systems with an attempt to indicate the presence of various removal processes. Evidence was given for biodegradation, sorption, and volatilization. The short duration of the experiment and the limited number of samples precluded mass balance calculations, so that firm conclusions about observed removals cannot be made. However, it did appear that many of the trace organic contaminants were removed during soil percolation, whereas others, such as chloroform, were not attenuated significantly by the passage through soil. Dichlorobenzenes were efficiently removed during percolation. Bacterial secondary metabolism was probably responsible for the low effluent concentrations. Sorption processes and volatilization losses were other mechanisms contributing to the observed trace organic removals. Further laboratory studies are needed to elucidate the importance of biodegradation, sorption, and other removal processes during soil percolation and to optimize design of land treatment systems for trace organics removal.

Trace Organics - Rice University:

The GC/MS results are presented in Tables 12 and 13. Table 12 contains all of the GC/MS results obtained. Table 13 contains only data for compounds with purity index greater than 800, or ones which have been matched by direct GC retention time. The concentrations of all 66 compounds in 2a are probably within ± 20% of the value shown, but if the purity were low and they were not confirmed by GC rention, at least, there is a low probability of qualitative correctness. Therefore, only the compounds in Table 13 need be discussed. In most cases where data are available, the unconditioned column was considerably more effective toward trace level removal than the conditioned column. This could be related to aeration and the viability of the aerobic population of bacteria in the soil surface. For some of the compounds the concentration actually increased, as with hexadecanol (No. 41). Some of these increases present in the effluent, but not in the influent, are probably due to bleed from the plexiglass column material. Without extensive testing it is not possible to sort out the effects of the hardware, etc., from the actual soil/bacteria removal or addition.

It is suggested that plastic columns be avoided when dealing with trace level organics. The plastic can bleed compounds into the water and sorb organics. Considerable comparison of the field and column data is called for before further interpretation is possible.

SUMMARY AND CONCLUSIONS:

Virus Adsorption: Viruses suspended in deionized water moved much farther through the soil than those suspended in tap water, while movement in sewage water was intermediate between those extremes. The salt content of the top water and sewage water promoted virus adsorption but evidently the organic compounds in sewage retarded adsorption. When viruses were suspended in chloride solution of K^+, Na, Ca^+ and Mg^{++}, virus adsorption increased as the cation concentration and valence increased. The depth of virus penetration could be related to ionic strength of the solutions. However, adsorption from KNO_3 was greater than adsorption from choride solutions, indicating the possibility of a specific anion effect. Adsorption from sewage water was about the same as from chloride solution of the same ionic strength, while adsorption from tap water was more than from chloride solution of the same ionic strength. More research will be needed to determine the component in tap water which stimulated the increase in virus adsorption. Viruses could not be detected in 10 mM solutions of $AlCl_3$ and $LaCl_3$ when sampled shortly after addition of stock poliovirus suspensions to reservoirs of those solutions. Possibly colloidal flocs adsorbed viruses and removed them from those solutions. Samples of $CaSO_4$ solutions also showed erratic virus counts. Extensive leaching of a column (8 days) that had been flooded with sewage water containing polio and echo virus resulted in little virus movement below the 80-cm depth. Two coliphages, f_2 and MS_2 were concentrated near the surface of the soil column when they were added to sewage water used to flood the columns. Leaching of phages with deionized water was limited as it was with poliovirus. In coliform studies, the coliform counts in the glass reservoirs and in the column head were lower than those in plastic storage containers of sewage. The counts increased as samples were extracted from columns at intervals down to the 20- to 40-cm depth. Below that depth the counts decreased as expected until very few passed the column outlet at 250 cm. Apparently some toxic substance in the glass reservoir, plastic lines or column head spaces damaged the bacteria and this damage was reversed as the bacteria moved through the soil to the 20- to 40-cm depth. Toxic compounds might be adsorbed by the upper 20- to 40-cm of soil.

N Removal Studies:

In nitrogen removal studies, using short dry periods of 2-3 hours to provide oxygen for nitrification during the last 3 days of the 9-day flooding period increased N removal slightly during 3 of the 9-day flooding and 5-day drying cycles. When normal flooding cycles were resumed 11 weeks later, the N removal was substantially increased for the first 3 cycles indicating that the experiment had been terminated prematurely. The short drying periods probably would increase N removal but would be difficult to use in a large field system.

Phosphate Studies:

Phosphate concentrations in the outflow from columns which released phosphate following a long dry period during 1976 and 1977, finally declined to levels below those in the incoming sewage. Short dry periods of 2 or 3 months did not seem to release additional phosphate. These studies showed that a long time of flooding is needed to return the systems to equilibrium after phosphate release was triggered by a very long dry period.

Virus Survival - Cooperative with Baylor:

Extraction of viruses from samples taken from recharge basins showed that most of the viruses were concentrated near the surface. This is in agreement with lab column studies and is further evidence that the columns are good models of the field system.

When poliovirus and echovirus were seeded in pipe sections filled with soil and buried in recharge basins, the survival rate was similar to that for viruses (from sewage) in soil samples from other parts of the basins. The rate of virus titer reduction was about 0.5 $\log_{10}$ units/day during the dry period. The rate of reduction of virus titer in small basins which had not been previously flooded with sewage was about the same. In most cases viruses could not be detected after 5 days of drying. Viruses survived longer during the flooding period. This is in agreement with lab studies showing longer survival times for viruses under anaerobic conditions than under aerobic conditions. Viruses buried in closed tubes also survived longer probably due to anaerobic conditions in the tubes. Viruses buried in centrifuge tubes with open ends survived longer than those in closed tubes, but not as long in open pipes. Drainage probably was restricted somewhat by the tubes so that less oxygen entered the soil in the tubes than in the surrounding soil. The laboratory value for rate of virus titer reduction at a constant 15% moisture and at 25° (about the soil temperature in the field study) was .24 $\log_{10}$ units per day. This is less than that for field samples from basins or open pipes but similar to reduction rates in the open centrifuge tubes.

These studies confirmed the laboratory evidence that viruses survive longer under anaerobic conditions and showed the importance of drying periods in reducing virus populations. The similar survival times of viruses occurring naturally in sewage water and seeded polio and echo in basin soil indicate that survival times of most enteroviruses found in sewage are similar and that poliovirus can be used as an indicator virus. These results can help extend findings from extensive laboratory studies on environmental and soil factors affecting virus survival.

Ceramic sampler - Cooperative with Baylor:

Laboratory studies showed that ceramic samplers constructed in our laboratory did not adsorb viruses when used to extract water samples for virus assays and could be used for that purpose. Commercially available samplers were unsuitable because they adsorbed viruses.

Endotoxin - Cooperative with Baylor:

Endotoxins released when bacterial cells are ruptured can be toxic to humans. Column studies showed that 90% of the endotoxins in sewage were adsorbed by 250 cm long soil columns. Endotoxins could be leached from the columns with deionized water indicating some potential for leaching by rainfall. Low concentrations of endotoxin were detected in field samples from Lubbock, TX, and Fort Devins, MA. Minimum allowable levels for groundwater have not been established.

Virus Adsorption by Different Soils - Cooperative with Baylor:

Poliovius and Echovirus were removed during 67 cm of travel through columns packed with Flushing Meadows loamy sand, Anthony sandy loam and Pomello sand, but passed through a column of Rubicon sand. Virus removal by different soils was inversely proportional to flow rates. This supports previous evidence that soil permeability may be the most important soil property affecting virus movement through different soils.

Trace Organics - Cooperative with Stanford University:

Outflow from soil columns flooded with secondary sewage effluent and tap water (all columns previously were flooded with sewage) were analyzed by 3 gas chromatographic procedures; volatile organic analysis (VOA), closed loop stripping analysis (CLSA), and solvent extract analysis (SEA). This study was conducted to give a general indication of trace organic movement in soil columns and to identify removal processes. Concentrations of most trace organics were substantially reduced during soil percolation but chloroform movement was not attenuated much by passage through the soil. Dichlorobenzenes were efficiently removed by percolation. Some compounds found in the sewage were not found in the column outflow while other compounds in the outflow were not found in the sewage. Some compounds were probably degraded completely in the soil and compounds in the outflow that were not found in sewage were probably humic acids or degradation byproducts. Evidence was found for removal of trace organics by biodegradation, sorption and volatilization. Some compounds previously removed were leached from the columns by tap water. Further laboratory studies are needed to determine the importance of these and other removal processes during soil percolation and to develop design criteria and management practices that would maximize trace organic removal.

Trace Organic - Cooperative With Rice University:

Two soil columns in the insulated shelter were flooded with secondary sewage effluent and 50 ℓ samples of the outflow were pumped through resin columns to concentrate trace organics. Samples were analyzed by a gas chromtograph mass spectrograph at Rice University. A number of compounds were isolated from the outflow. A column that had been conditioned by applications of sewage for several days before sampling was considerably more effective in removing trace organics than the column flooded one day before sampling began.

PUBLICATIONS:

1. Lance, J. C. and Gerba, C. P. Virus removal from sewage during high-rate land filtration. Proc. of the Water Reuse Symposium, Washington, D. C., March 1979. 3:2282-2290. 1979.

2. Goyal, Sagar M., Gerba, C. P., and Lance, J. C. Movement of endo toxin through soil columns. Jour. of Applied Bacteriology. (In Press)

3. Lance, J. C. and Gerba, C. P. Poliovirus movement during high rate land filtration of sewage water. Jour. of Envir. Quality. (In Press)

4. Wang, D-Shin, Lance, J. C., and Gerba, C. P. Evaluation of various soil water samplers for virological sampling. Appl. & Environ. Microbiology. (In Press)

PERSONNEL: J. C. Lance, Gladys Auer; Cooperators, Baylor College of Medicine, C. P. Gerba, C. J. Hurst and De-Shin Wang. Stanford University, E. J. Bouwer. Rice University, Mason Thompson, Steve Hutchins

Table 1. Solutions used to study the effect of different ions on poliovirus adsorption. Solutions are listed in the sequence in which they were applied.

Salt	Concentrations
NaCl	1 mM, 10 mM
KCl	1 mM, 20 mM
Deionized H_2O	-----------
$CaCl_2$	2 mM, 20 mM
$MgCl_2$	1 mM, 10 mM
$AlCl_3$	1 mM, 10 mM
$CaSo_4$	1 mM, 10 mM
KNO_3	1 mM, 3 mM, 10 mM
Tap H_2O	-----------------
Sewage	-----------------

Table 2. Coliphages at different depths in a column flooded with phage-enriched sewage

Column Depth cm	Coliphages remaining PFU/mℓ*	
	F_2	MS_2
0	11,350	13,400
2	2,970	1,590
5	415	25
10	5	10
20	5	5

* Averages for 2 sampling dates

Table 3. Coliphages at different depths in soil columns flooded with deionized water.

Column depth cm	Sampling time after flooding PFU/mℓ					
	8 hrs		14 hrs		24 hrs	
	F_2	MS_2	F_2	MS_2	F_2	MS_2
0	185	250	5	0	5	10
2	225	160	60	50	5	0
5	210	135	75	60	5	0
10	100	55	185	130	0	0
20	35	35	215	0	55	0
40	0	0	0	0	0	0

Table 4. Coliforms at different depths in a column flooded with sewage.

Depth cm	Sample date - November 6	7	8	9	14	15	16
Effluent	$6.2x10^{6}$	$2.3x10^{6}$	$3.0x10^{5}$	$2.3x10^{4}$	$6.0x10^{3}$	$3.0x10^{4}$	$2.0x10^{4}$
Col. head	$3.5x10^{6}$	$2.0x10^{3}$	$7.5x10^{3}$	$2.0x10^{3}$	---	6.10^{4}	$3.3x10^{4}$
2	$4.6x10^{6}$	$1.5x10^{3}$	$6.0z10^{3}$	$4.0x10^{3}$	$5.2x10^{4}$	$2.5x10^{4}$	$3.5x10^{4}$
10	$3.8x10^{6}$	$8.0x10^{3}$	$4.6x10^{4}$	$4.9x10^{4}$	$8.5x10^{4}$	$2.0x10^{4}$	$4.7x10^{4}$
20	$3.3x10^{5}$	$2.0x10^{5}$	$9.0x10^{4}$	$5.5x10^{4}$	$1.3x10^{5}$	$1.0x10^{4}$	$1.4x10^{6}$
40	$6.8x10^{2}$	$1.9x10^{4}$	$7.0x10^{4}$	$9.0x10^{4}$	$5.5x10^{4}$	$1.0x10^{5}$	$1.6x10^{5}$
80	0	9	$3.5x10^{2}$	$3.1x10^{2}$	$9.5x10^{3}$	$3.8x10^{3}$	$3.2x10^{3}$
130	0	0	0	0	$3.1x10^{2}$	$7.0x10^{1}$	5
250	0	0	0	0	$1.5x10^{1}$	$3.5x10^{2}$	0

Table 5. Drainage volumes during short dry periods in a 9-day flooding cycle

	Drain time (min)	Drain volume (Mℓ) for Column No. 2	3	4	8
		Flooding date - 18 Jan - 26 Jan			
	200	360	280	407	347
	175	351	210	365	266
	115	246	128	252	175
Total	490	956	618	1024	788
		Flooding date - 31 Jan - 08 Feb			
	170	325	211	321	234
	190	385	221	379	264
	190	368	255	382	284
Total	550	1078	687	1082	782
		Flooding date - 14 Feb - 22 Feb			
	110	206	104	221	155
	160	287	168	285	249
	175	288	168	352	255
Total	435	781	440	858	659

Table 6. Nitrogen removal rates of columns used for short dry period study.

Cycle date	N removal (%) Col. 2	Col. 4	Col. 8
01/02-01/18	52.5	10.4	42.6
01/18-01/31	-20.7	-1.5	-31.1
01/31-02/14	56.6	53.9	18.2
02/14-03/01	36.2	44.7	51.1
03/01-03/10	-8.8	12.0	21.5
05/31-06/12	69.4		82.7
06/12-06/26	47.7		57.7
06/26-07/10	64.7		61.2
07/10-07/24	39.4		49.9
07/24-08/09	38.9		15.9
11/06-11/20	65.6		67.7
11/20-12/03	--		--
12/04-12/17	26.3		49.8
12/18-01/01	17.1		47.2

Table 7. Viruses eluted from soils in groundwater recharge basins flooded with sewage water.

Soil depth (cm)	Primary effluent basin	Secondary efluent basin	
	PFU/200g Soil		
	Day 1	Day 1	Day 3
0.0 - 2.5	101	35	6
2.5 - 10.0	6	3	2
10.0 - 25.0	5	1	1

Table 8. Reduction in soil moisture and virus titer during the drying portion of the sewage application cycle

Soil samples containing virus	Average % reductions per day, between sampling dates		Rate of reduction invirus titer (log_{10} units/day)
	Moisture content	Virus titer	
Feld study during fall weather conditions			
Polio 1 in small basin	34.7	33	0.52
Polio 1 buried in pipe sections	5.0	31	0.49
Echo 1 buried in pipe sections	10.5	28	0.45
Indigenous virus in large basin	13.8	30	0.48
Polio 1 buried in small open tubes	7.8	13	0.11
Echo 1 buried in small open tubes	6.4	19	0.28
Field study during winter weather conditions			
Indigenous virus	24.7	30	0.23

Table 9. Soil Characteristics

Soil type	Particle size distribution (%) Sand	Silt	Clay	Location	pH	Cation exchange capacity (meq/100g)	Organic matter (%)
Flushing Meadows loamy sand	89	8	3	Arizona	7.8	--	0.9
Rubicon sand	92	4	4	Michigan	5.5	5.6	0.4
Pomello sand	89	8	3	Florida	7.1	6.5	3.64
Anthony sand loam	77	10	13	Arizona	8.2	4.2	0.27

Table 10. Compounds identified by CLSA in soil influents and effluents.*

		Average Influent Concentration ng/l	Average Effluent Concentration ng/l
Compounds Present in Both Secondary Sewage and Effluents			
1,3-dichlorobenzene	$C_6H_4Cl_2$	120	35
1,4-dichlorobenzene	$C_6H_4Cl_2$	820	120
1,2-dichlorobenzene	$C_6H_4Cl_2$	760	105
2,2,4-trimethyl-penta-1,3-diol-di-isobutyrate	$C_{16}H_{30}O_4$	500	120
2,6-di-t-butyl-4-bromo-methyl phenol	$C_{15}H_{23}OBr$	590	560
Cadinene	$C_{15}H_{24}$	150	30
4 Unknowns		-	-
Compounds Present Only in Secondary Sewage			
1,4-cineol	$C_{10}H_{18}O$	1200	-
1,2,4-trichlorobenzene	$C_6H_3Cl_3$	210	-
neoisothujyl alcohol	$C_{10}H_{12}O_1$	210	-
m-ethylphenyl acetate	$C_{10}H_{14}O$	310	-
4 Unknowns		-	-
Compounds Present Only in Column Effluents			
2,4,4-trimethyl pentene	C_8H_{16}	-	560
2,6-di-t-butyl-4-methyl phenol	$C_{15}H_{24}O$	-	110
5 Unknowns			

*Compounds identified by comparison of mass spectra with those contained in: E. Stenhagen, S. Abrahamson, F. W. McLafferty (eds.), Registry of Mass Spectral Data, John Wiley & Sons, New York, 1974.

Table 11. Compounds identified by SEA in soil column influents and effluents.*

		Average Influent Concentration ng/l	Average Effluent Concentration ng/l
Compounds Present in Both Secondary Sewage and Effluents			
2,3,4,5-tetrachloroanisole	$C_7H_4OCl_4$	15	15
pentachloroanisole	$C_7H_3OCl_5$	70	40
lindane	$C_6H_6Cl_6$	90	15
diisobutyl phthalate	$C_{16}H_{22}O_4$	40	20
DDT	$C_{14}H_9Cl_5$	40	40
diethylhexyl phthalate	$C_{24}H_{38}O_4$	70	130
di-n-butyl phthalate	$C_{16}H_{22}O_4$	110	15
alkylated phenol	$C_{14}H_{22}O$	230	70
6 Unknowns		-	-
Compounds Present Only in Secondary Sewage			
2,3,5,6-tetrachloroanisole	$C_7H_4OCl_4$	110	-
3 Unknowns		-	-
Compounds Present Only in Column Effluents			
dimethyl phthalate	$C_{10}H_{10}O_4$	-	20
1 Unknown		-	-

*Compounds identified by comparison of GC retention times with standards or by mass spectra comparison with those contained in: E. Stenhagen, S. Abrahamson, F. W. McLafferty (eds.), Registry of Mass Spectral Data, John Wiley & Sons, New York, 1974.

Table 12. Analysis of soil column samples by Rice University.

IDENTIFICATION OF ORGANIC COMPOUND	Max Purity[1]	Retention Verified	Sewage Effluent[2]	Conditioned "A"	Unconditioned "B"
1. tetrachloroethylene	970	*	–	–	–
2. m-xylene	854	*		0.17	0.15
3. 6-methyl-5-nonen-4-one	634			0.76	0.44
4. p-ethyltoluene	776	*	0.10		
5. 2-ethyl-1-hexanol	968			0.31	0.19
6. 1-methyl-4-isopropyl-7-oxabicyclo (2.2.1)heptane	457		1.23		
7. trans-decahydronaphthalene	847		0.02		
8. dimethyltrisulfide	806		0.10		
9. p-dichlorobenzene	946	*	0.11		
10. o-dichlorobenzene	923	*	0.12	0.03	0.01
11. 3,3,5-trimethylcyclohexanone	882	*	0.23		
12. 4-methylcyclohexanol	603			0.03	–
13. o-cresol	912	*	40.00		
14. 1,2-dimethyl-3-isopropenylcyclopentanol	482		–	0.08	0.03
15. 3,3,5-trimethyl-2-cyclohexen-1-one	937		2.19	0.82	0.13
16. (2,2-dimethoxyethyl)benzene	694		0.08	0.05	0.01
17. α-(1-methylamino)ethyl benzenemethanol	586		0.08		
18. 2-methyl-2H-benzotriazole	868			0.04	0.09
19. 4-chlorobenzenamine	389				
20. dimethyltrisulfide	546		0.06		
21. α,4-dimethylbenzenemethanol	528		0.29		
22. 1-(isooctyloxy)-2-methyl-2-propanol	505		0.37		
23. dichloromethoxy benzene	397			0.18	0.11
24. 1H-indole	902	*	0.82	0.20	0.11
25. p-t-pentylphenol	704	*	1.70		
26. 1,5-bis(t-butyl)-3,3-dimethylbicyclo (3.1.0)hexan-2-one	536		0.16	0.26	
27. di-t-butyl-p-benzoquinone	600	*	0.17	0.20	0.33
28. m-hydroxybenzoacetic acid	449			–	
29. trans-1,2-dimethyl-3-phenylaziridine	321			–	
30. di-t-butyl-p-cresol	750	*	0.21		
31. 1,2,3-trichloro-4-methoxybenzene	738			0.22	–
32. 3-methyl-1,1'-biphenyl	857		1.34		
33. 1-phenyl-1,2-ethanediol	795		0.17		

[1] Max Purity: An indication of the "closeness-of-fit" of the spectra. Scaling: 800-1000: Very Close, Good Fit 600-800: Probable Fit 400-600: Maybe 0-400: Probably Not

[2] All units given in ppb. Those designated by "-" imply inability to measure peaks.

Table 12. (Cont'd) Analysis of soil column samples by Rice University.

IDENTIFICATION OF ORGANIC COMPOUND	Max Purity[1]	Retention Verified	Sewage Effluent[2]	Conditioned "A"	Unconditioned "B"
34. 1,1,3,3-tetramethylbutylphenol	929	*	1.94	0.60	
35. (methylsulfonyl)methylbenzene	614				0.44
36. imidazolidinone	656			4.16	3.09
37. 2-(methylthio)benzothiazole	752		0.65		
38. 4-propoxyphenol	413			2.65	
39. phenylbenzoate	943				3.46
40. 2,2,3,3-tetramethylbutylphenol	707		4.33		
41. hexadecanol	679	*	1.72	3.67	4.16
42. 2-(4-phenoxyphenoxy)ethanol benzoate	618			1.34	0.03
43. 3,4-dimethoxy benzeneethanamine	389		0.37		
44. 1-(ethenyloxy)decane	544			4.72	
45. tridecanol	515				3.40
46. 2-methyl-2-propyl-1,3-propanediol, dicarbamate	755			1.57	
47. 2-(4-t-butylphenoxy)ethanol	501		0.26		
48. (2-hexyloctyl)cyclopentane	444			10.09	
49. 2-methyl-1-nitrosopiporidine	445				8.31
50. 1,naphthalenol, methyl carbamate	452				
51. 1-(p-t-butylphenyl)ethanone	516				
52. ethyl-(5-ethoxy-4-pentenuate)	354			2.89	
53. 2-(2-methoxyethoxy)ethanol	519		3.85	3.09	2.56
54. 2-t-butylphenyl-2,2-dimethylpropanoate	361		0.86		
55. 3-methoxy-1H-indazole	314				5.05
56. 1,1'-methylenebis(oxy)biscyclohexane	646			1.68	
57. 3,9-diethyl-6-tridecanol	414		8.23		1.73
58. 4,4 -isopropylidenebisphenol	374			4.01	
59. 1-(2,5-dichlorophenyl)ethanone	612		4.40		4.35
60. dihydro-5-methyl-2(3H)furanone	443		4.52	5.04	
61. 2-butyl-1,3,2-dioxarsenane	611		8.80		3.79
62. triphenylphosphate	461			-	-
63. (t-butoxy)methyl benzene	561			1.39	4.35
64. octyl-10-undecenuate	328			0.69	-
65. 1-bromotetradecane	186			0.19	6.37
66. 4(1H)-pteridinone	436		-		

[1] Max Purity: An indication of the "closeness-of-fit" of the spectra. Scaling: 800-1000: Very Close, Good Fit 600-800: Probable Fit 400-600: Maybe 0-400: Probably Not

[2] All units given in ppb. Those designated by "-" imply inability to measure peaks.

Table 13. Analysis of soil column samples by Rice University.

IDENTIFICATION OF ORGANIC COMPOUND	Max Purity[1]	Retention Verified	Sewage Effluent[2]	Conditioned "A"	Unconditioned "B"
1. tetrochloroethylene	970	*	-	-	-
2. m-xylene	854	*	-	.17	.15
4. p-ethyltoluene	776	*	.10	-	-
5. 2-ethyl-1-hexanol	968		-	.31	.19
7. trans-decahydronaphthalene	847		0.02	-	-
8. dimethyltrisulfide	806		0.10	-	-
9. p-dichlorobenzene	946	*	0.11	-	-
10. o-dichlorobenzene	923	*	0.12	.03	.01
11. 3,3,5-trimethylcyclohexanone	882	*	0.23	-	-
13. o-cresol	912	*	40.0	-	-
15. 3,3,5-trimethyl-2-cyclohexen-1-one	937		2.19	.82	.13
18. 2-methyl-2H-benzotrizole	868		-	-	.09
24. 1H-indole	902	*	.82	.20	.11
25. p-t-pentylphenol	704	*	1.71	-	-
27. di-t-butyl-p-benzoquinone	600	*	0.17	.20	-
30. di-t-butyl-p-cresol	750	*	0.21	-	-
32. 3-methyl-1,1'-biphenyl	857		1.34	-	-
34. 1,1,3,3-tetramethylbutylphenol	929	*	1.94	.60	-
39. phenylbenzoate	943				3.46
41. hexadecanol	679	*	1.72	3.67	4.16

[1] Max Purity: An indication of the "closeness-of-fit" of the spectra. Scaling: 800-1000: Very Close, Good Fit 600-800: Probable Fit 400-600: Maybe 0-400: Probably Not

[2] All units given in ppb. Those designated by "-" imply inability to measure peaks.

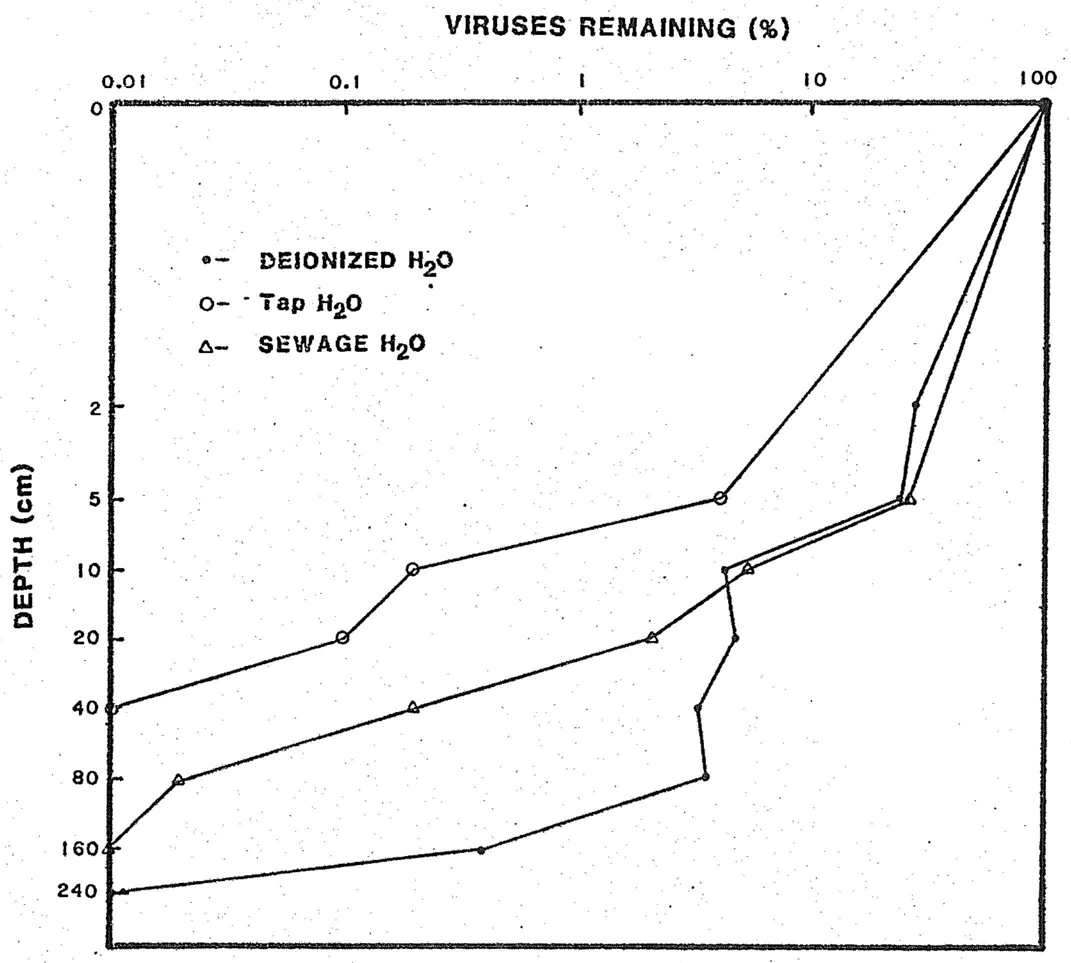


FIG. 1. Virus adsorption by soil columns from deionized water, tap water and secondary sewage effluent.

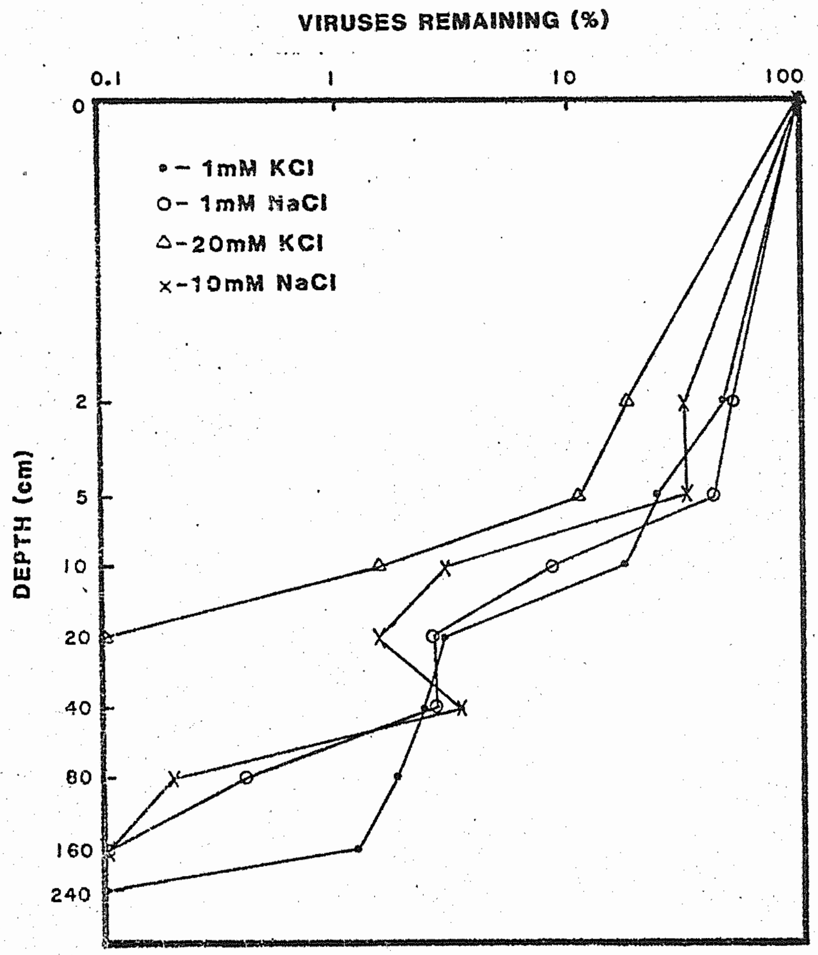


FIG. 2. Virus adsorption by soil columns from NaCl and KCl solutions.

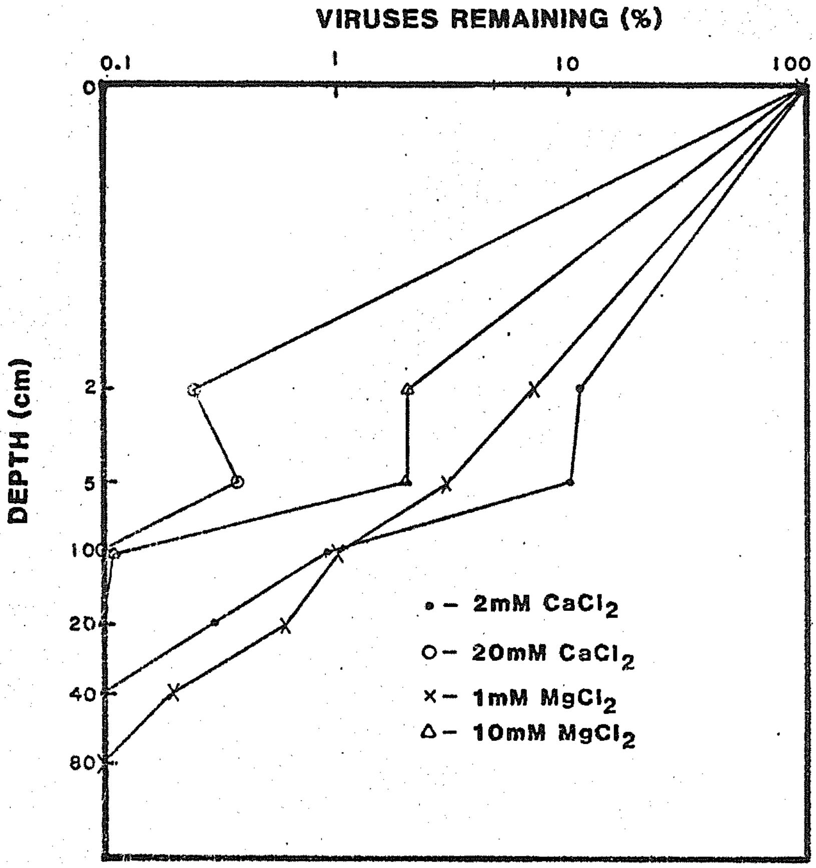


FIG. 3. Virus adsorption by soil columns from $CaCl_2$ and $MgCl_2$ solutions.

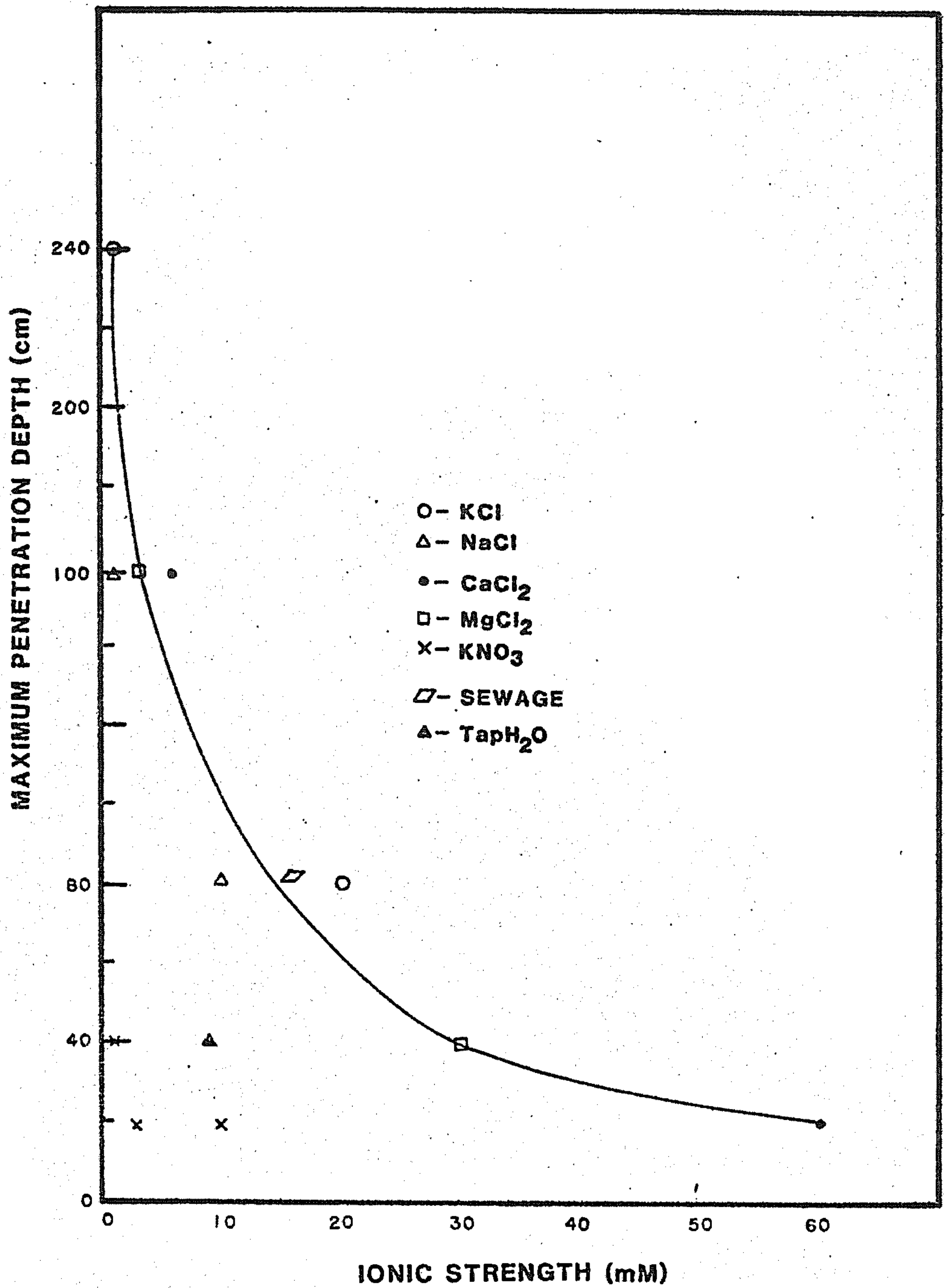


FIG. 4. The effect of ionic strength on the maximum depth of penetration by viruses in soil columns.

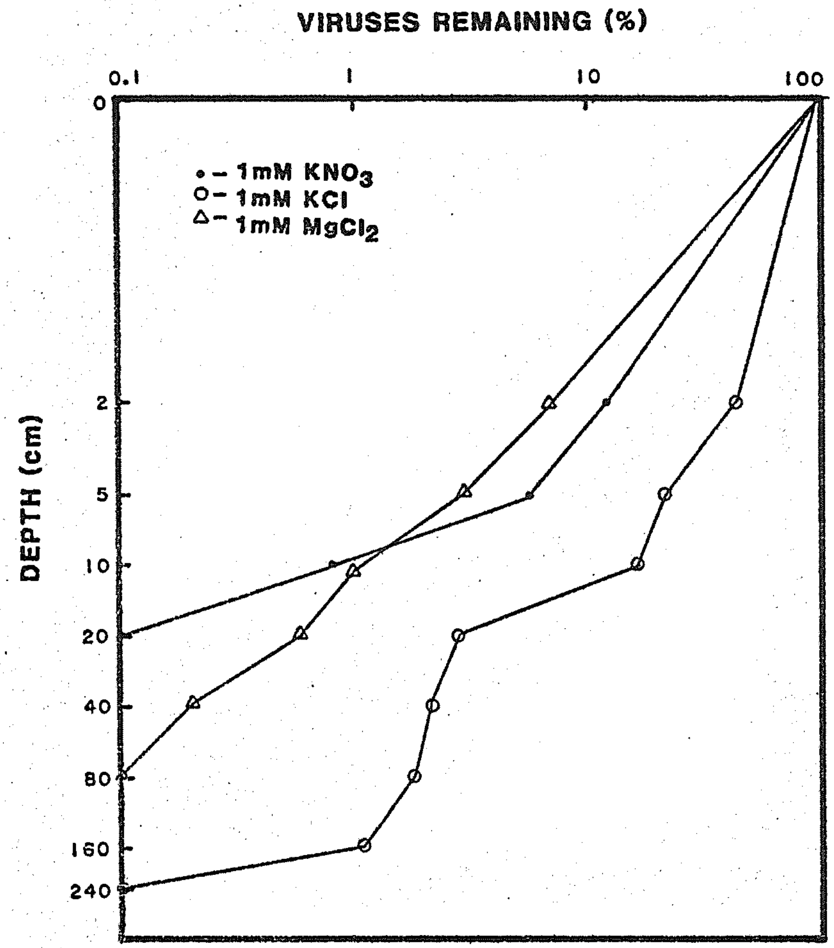


FIG. 5. Virus adsorption from 1 mM solutions of KNO_3, KCl and $MgCl_2$.

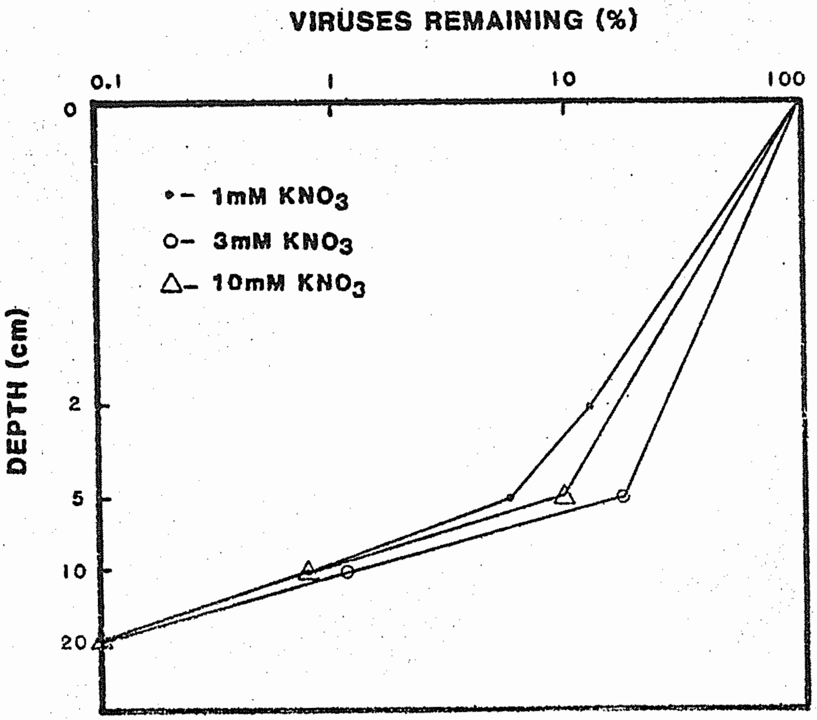


FIG. 6. Virus adsorption from soil columns by KNO_3 solutions.

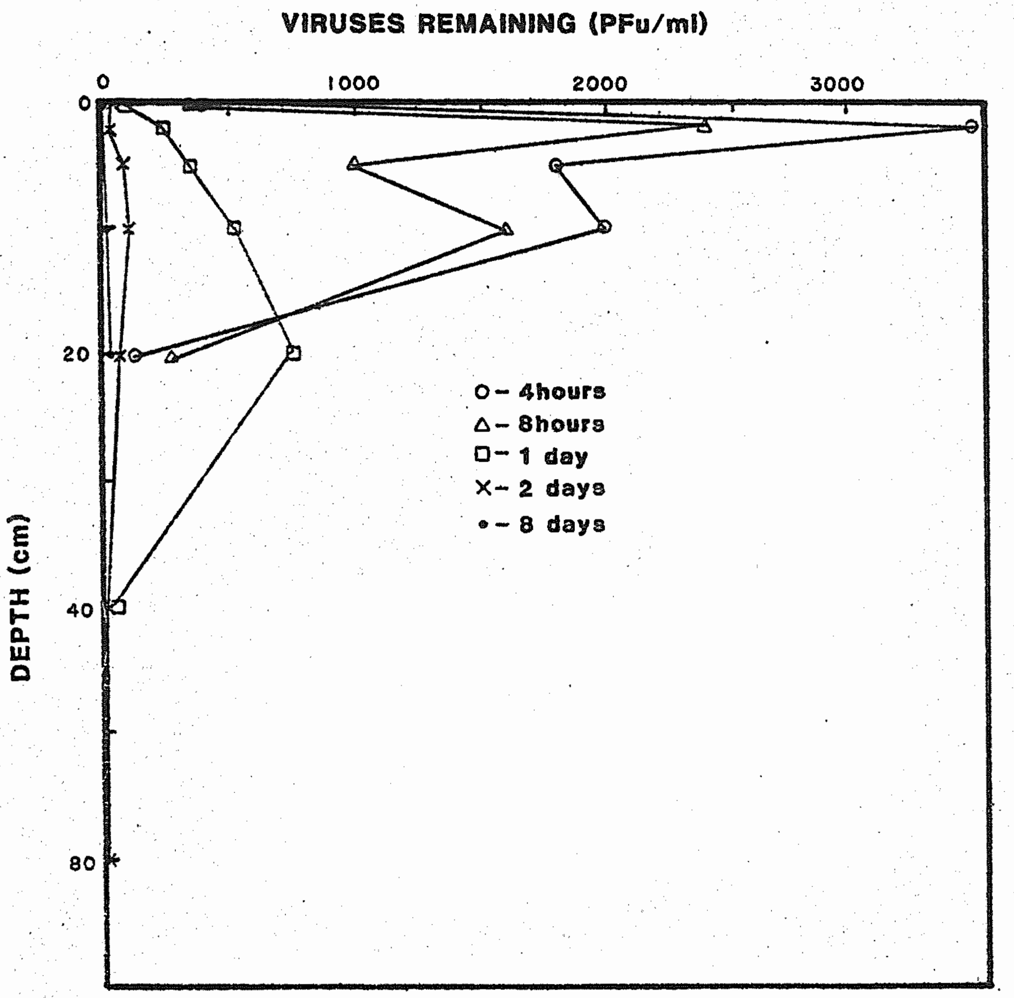


FIG. 7. Desorption of viruses from soil columns by extensive flooding with deionized water.

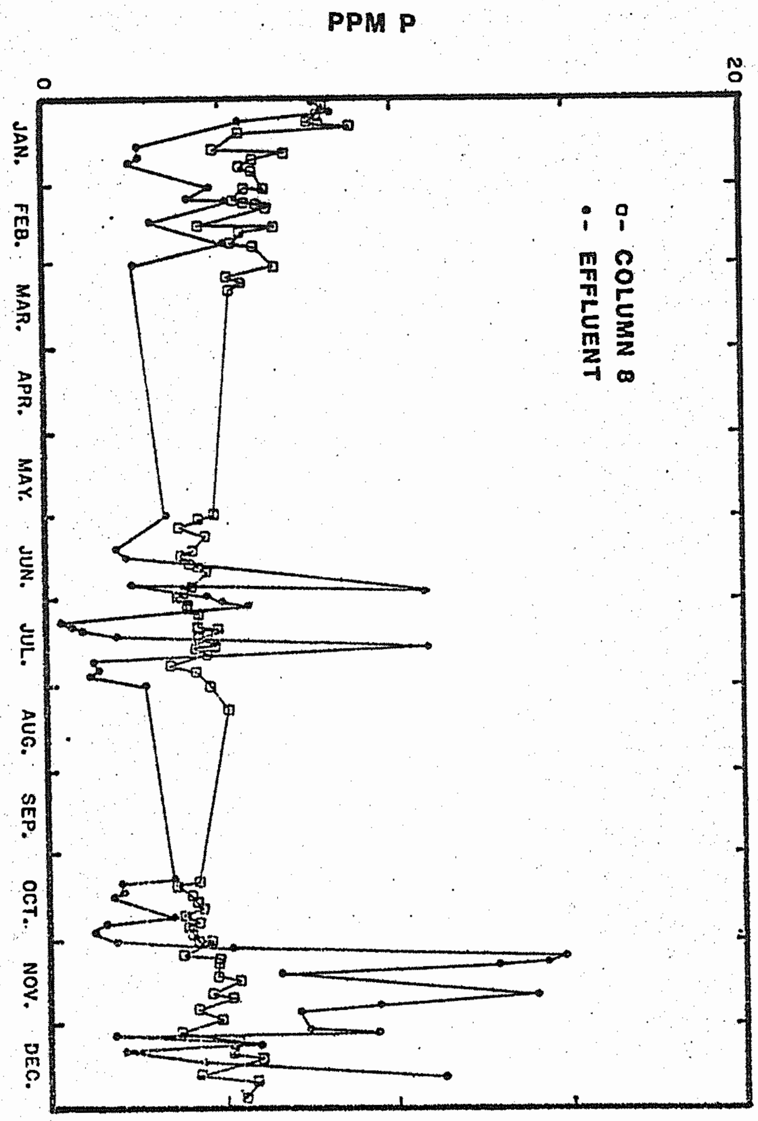


FIG. 8. Phosphate concentrations in water from soil columns intermittently flooded with sewage following 18 months of drying.

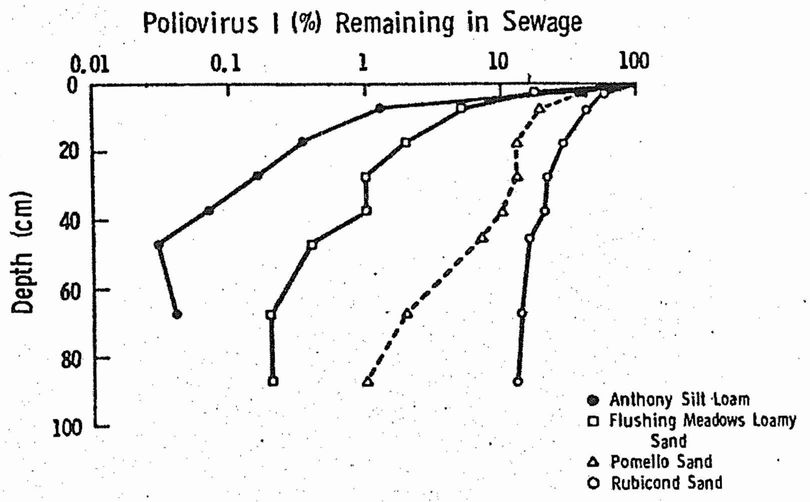


FIG. 9. Removal of poliovirus 1 by 4 soil columns.

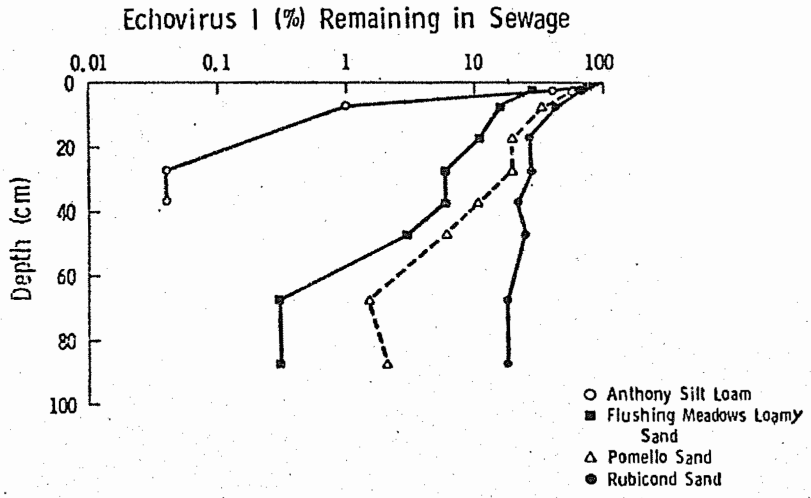


FIG. 10. Removal of echovirus 1 by 4 soil columns.

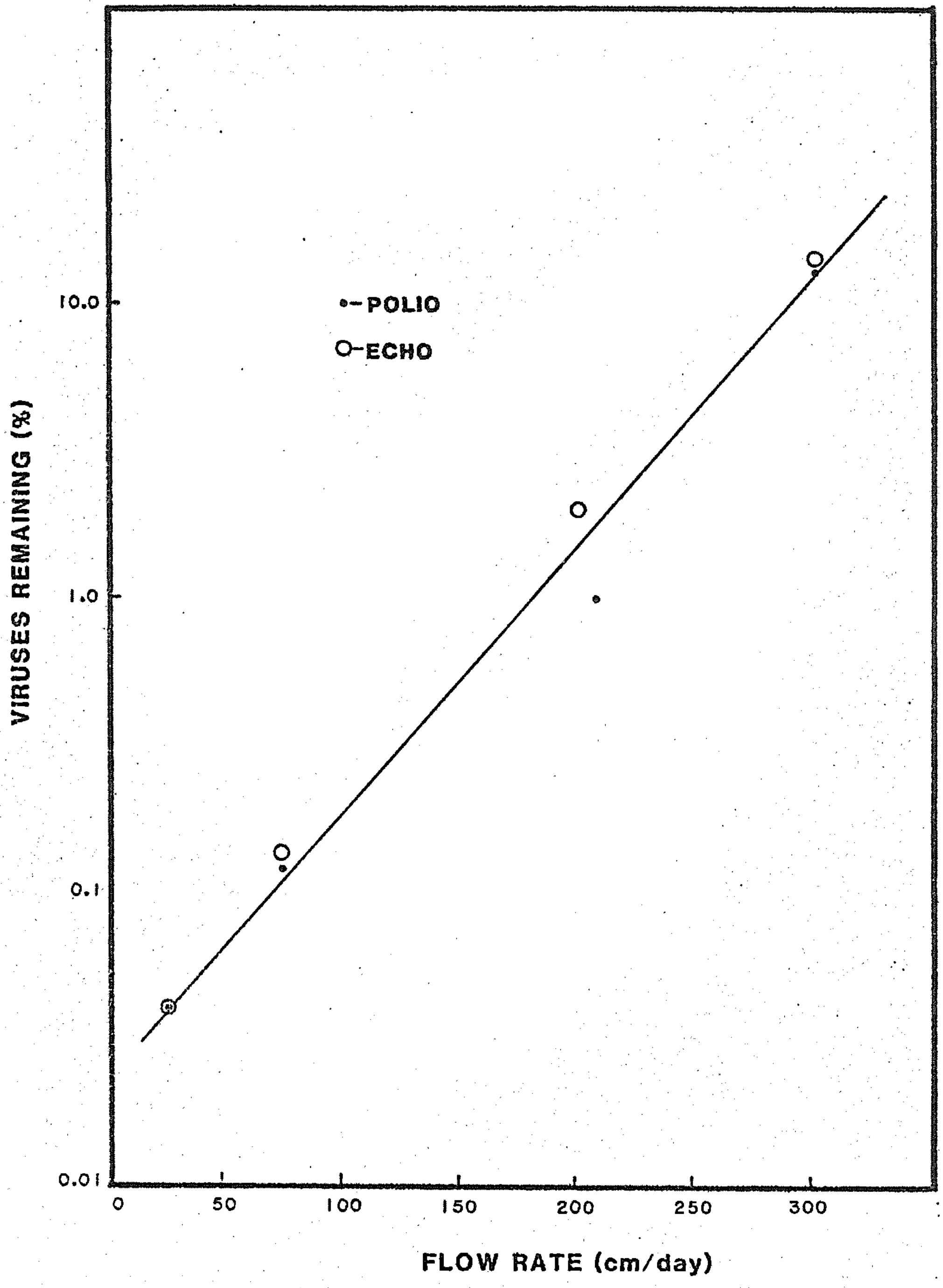


FIG. 11. The effect of infiltration rate on virus adsorption by columns packed with different soils.

FIGURE 11.

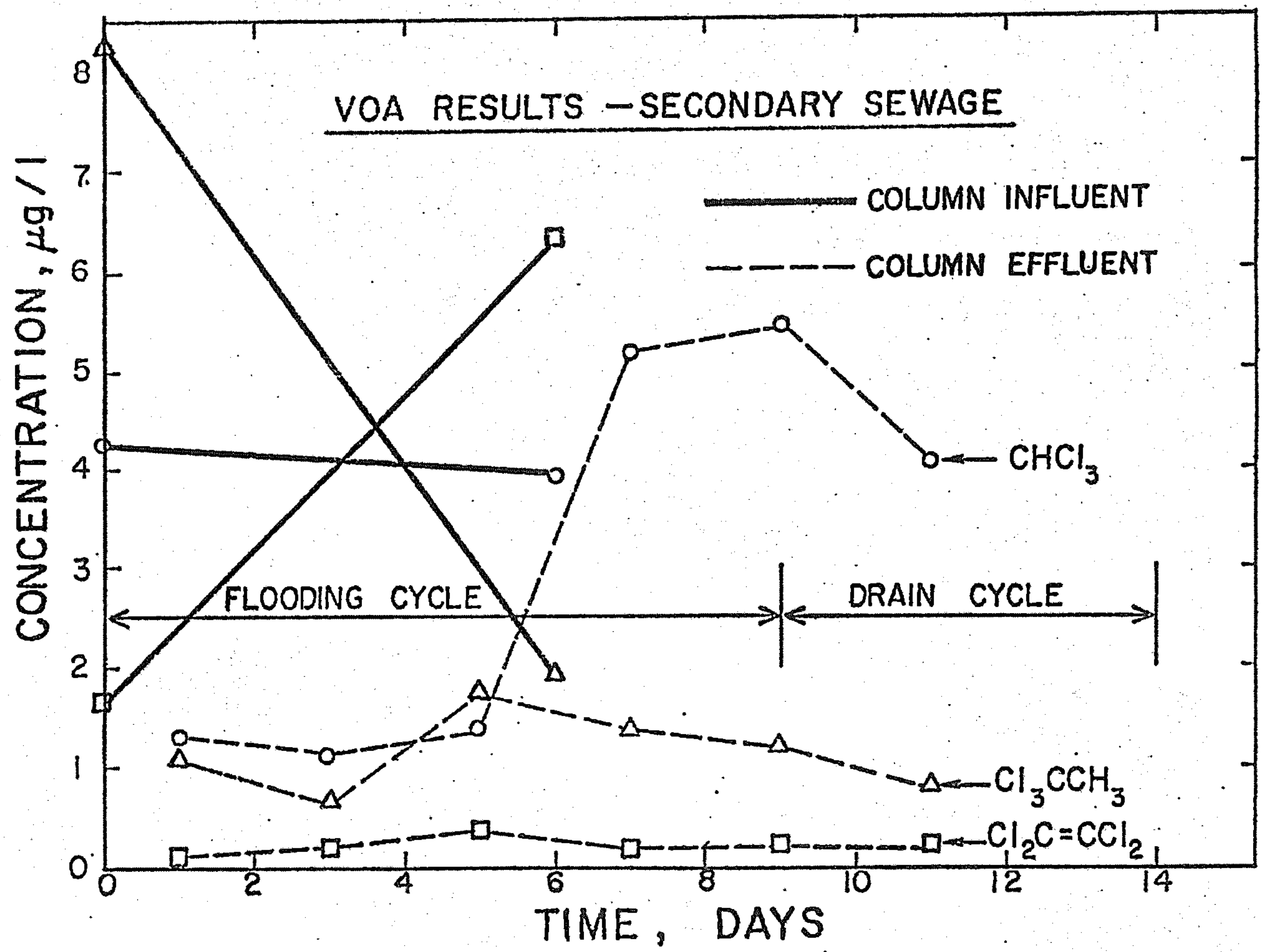


FIG. 12. Trace organics detected by VOA analysis in the outflow from a soil column flooded with secondary sewage effluent.

TITLE: USE OF FLOATING MATERIALS TO REDUCE EVAPORATION FROM WATER SURFACES

NRP: 20810 CRIS WORK UNIT: 5510-20810-002

INTRODUCTION:

Long-range durability and efficiency studies, which started at the Granite Reef test site in June 1970 after a calibration period in 1969, were terminated the first of April 1979. Floating covers tested on the 9-ft-diameter stock tanks during the study period consisted of foamed rubber, foamed wax blocks, and three continuous wax covers. Efficiencies for these covers ranged from 36 to 84 percent, and exposure times varied from 3.2 to 8.0 years. Visual observations of the performance of a wax cover on the lined pond at Granite Reef were also discontinued in April 1979.

Field evaluation of the foamed rubber covers, the first located on a tank in 1971 in southwestern Utah, and four others in Arizona in 1974, was continued. Some additional information was obtained regarding performance of some 50 to 60 field operational covers located on tanks on the Arizona Strip and near Safford, Arizona.

PROCEDURE:

Evaluation of the covers on the Granite Reef tanks was the same as in previous years (evaporation from a treated tank being compared to that from an identical untreated tank).

Only visual observations of the field-installed foam rubber covers were made. Evaporation measurements were not recorded.

RESULTS AND DISCUSSION:

Granite Reef Studies: Monthly evaporation from the open tank (which was used as a standard), along with the monthly efficiencies, in percent, of the various floating covers for the periods of testing are presented in Table 1. Also shown are the total depth of water evaporated from the open tank, from those with floating covers for corresponding periods, the amount of water saved, the average evaporation reduction efficiency for the entire period, and the total days of exposure for each of the floating covers tested.

Average evaporation reduction efficiency ranged from 36 percent over an 8-year period for the foamed wax blocks which covered about 60 percent of the water surface, to 84 percent over a 4-year period for the foamed rubber cover which covered almost 95 percent of the water surface. Total days of exposure ranged from 1170 for the first continuous wax cover to 2910 for the foamed wax blocks. All of the continuous wax covers showed signs of deterioration and reduced efficiency at the end of their exposure periods while the foamed wax blocks maintained essentially the same efficiency throughout the 8 years of testing and showed no visual signs of weathering.

Two of the continuous wax covers were as efficient as the foamed rubber cover during the first 4 years of exposure, but efficiency began to decrease after 5 years and average efficiency for the 6 to 7 years of exposure was 80 percent. The other continuous wax cover consisted of a higher melting point wax which tended to crack as temperatures cooled in the fall, and it would not reform into a continuous sheet until late in the spring. It was removed after a little more than 3 years and average efficiency was only 69 percent. Other studies mentioned in previous annual reports indicated that the continuous wax covers were less effective in colder climates, and their use should be limited to vertical walled tanks in hot desert areas like Phoenix.

Although more water was saved by the foamed rubber cover in 4 years than by the foamed wax blocks in 8 years, the cost of the cover must be considered to determine the most practical cover. Costs of the five covers at the time of their purchase, and the cost of the water saved, is presented in Table 2. As shown for the period studied, the continuous wax covers of 120°-125° melting point wax provided the lowest cost water. Although these covers were deteriorating at the end of the study it would appear two or three covers could be used to extend the life beyond the 15-year expected life of the foamed rubber cover, and at a lower overall cost. However, costs change so rapidly it is difficult to determine what relative costs will be at the end of 6 years, and the wax covers are limited to a very small hot desert region.

The wax cover on the lined pond appeared the same in April 1979 as during the previous year, but measurements of efficiency were not made.

<u>Field Studies</u>: Five experimental foamed rubber covers remained functional during 1979.

Beaver Dam Tank, southwest of St. George, Utah, installed November 1971. The tank is still actively being used and the cover is in good condition. The material reportedly has become slightly brittle but is still functional.

Frasier Well and Shipley Well Tanks, Hualapai Indian Reservation, installed May 1974. Both covers are functioning satisfactorily. The Shipley Well cover was patched in early 1979.

Glover Ranch Tank, south of Safford, Arizona (Bureau of Land Management), installed September 1974. The cover has been used continually since 1974 and is in excellent condition. The BLM District at Safford has a continuing program of developing water supplies which has included about 30 floating covers. To date the covers have functioned as intended.

Hughes Ranch Tank, south of Rye, Arizona (Tonto National Forest), installed November 1974. A catchment, installed in 1977, supplies water at the site. Heavy precipitation during January and February 1979 filled the tank and the cover floated off. No overflow protection had been installed. The cover was trampled by the livestock but was salvaged by cleaning, trimming, and patching five holes (largest about 1 ft x 1 1/2 ft). Two people were able to rehabilitate and replace the cover on the tank in 45 minutes. Three wires were placed diagonally across the tank to prevent removal in the future.

The Bureau of Land Management on the Arizona Strip has installed 20 to 25 covers over the past 4 years. They had problems with one in 1978 and another in 1979. The cover in 1979 was installed in June and was found to be broken up in small pieces in November. The company supplying the material is investigating the cause of failure. Possible causes may be improper curing of the sheet goods or shipment of the wrong sheeting from the factory. All other covers are working satisfactorily.

SUMMARY AND CONCLUSIONS:

After 8 years, the long-range durability and efficiency studies at the Granite Reef test site were terminated in April 1979. Floating covers tested on the 9-ft-diameter stock tanks during the study were foamed rubber, foamed wax blocks, and three continuous wax covers. Evaporation reduction efficiencies for these covers ranged from 36 percent for the foamed wax blocks which covered about 60 percent of the water surface, to 84 percent for the foamed rubber cover which covered about 95 percent of the surface. Total days of exposure ranged from 1170 days for a continuous wax cover, to 2910 days for the foamed wax blocks.

The foamed rubber and foamed wax blocks did not show any signs of deterioration, while evaporation reduction efficiency of all three continuous wax covers began to decrease prior to termination of the study period. The continuous wax covers are also effected by cold temperatures, and are most effective on vertical walled tanks in hot desert climates.

Based on the amount of water saved during the study and the cost of materials at the time of installation, the continuous wax covers provided the lowest cost water at $.26 to $.34 per 1000 gallons. However, cost relationships change rapidly and long-term durability, evaporation reduction efficiency, and climatic range of useability should be considered along with costs when determining the most practical cover to use.

Experimental, field operational, foamed rubber covers continued to function satisfactorily during 1979. Two isolated incidences of cover deterioration have occurred (some 50 to 60 in the field). The cause of the problems are being investigated by the company supplying the sheet material.

PERSONNEL: Keith R. Cooley, Allen R. Dedrick

Table 1. Evaporation reduction efficiency of floating covers on 9-ft-diameter stock tanks at Granite Reef.

Date Mo Yr	Evaporation from open tank in centimeters	Evaporation Reduction Efficiency of Covers in Percent				
		Continuous wax (120-135)	Continuous wax (120-125)	Continuous wax (120-125)	Foamed Rubber	Foamed wax blocks
Jun 70	36.93					32
Jul "	41.82					35
Aug "	34.96					39
Sep "	23.62					36
Oct "	21.18					37
Nov "	10.72					33
Dec "	10.00					26
Jan 71	9.48	29a				29
Feb "	15.02	21				33
Mar "	20.93	21				35
Apr "	24.94	30				40
May "	37.30	37b	78			43
Jun "	41.91	65	99			43
Jul "	44.50	97	99			45
Aug "	29.70	94	98			38
Sep "	32.08	95	97			36
Oct "	8.24	80	82			34
Nov "	15.79	44	71			27
Dec "	8.06	23	50			14
Jan 72	15.06	32	29			23
Feb "	13.04	56	69			33
Mar "	29.43	72	91			36
Apr "	28.78	63	92			36
May "	32.98	74	94			38
Jun "	43.12	94	98	15		42
Jul "	37.92	98	98	90		43

Table 1. Evaporation reduction efficiency of floating covers on 9-ft-diameter stock tanks at Granite Reef (continued).

Date Mo	Yr	Evaporation from open tank in centimeters	Evaporation Reduction Efficiency of Covers in Percent: Continuous wax (120-135)	Continuous wax (120-125)	Continuous wax (120-125)	Foamed Rubber	Foamed wax blocks
Aug	72	35.73	97	97	97		37
Sep	"	37.74	98	99	99		40
Oct	"	5.61	89	97	91		57
Nov	"	6.67	58	72	48		41
Dec	"	6.50	48	47	33		28
Jan	73	6.68	55	52	30		28
Feb	"	6.78	50	50	48		30
Mar	"	4.23	-	69	74		44
Apr	"	22.59	62	76	63		42
May	"	37.29	65	92	93		54
Jun	"	42.57	87	98	98		29
Jul	"	13.10	93	97	100		27
Aug	"	33.42	97	99	99		30
Sep	"	35.28	92	99	100		26
Oct	"	25.15	51	78	96		34
Nov	"	8.46	27	29	72		15
Dec	"	11.19	29	37	50		25
Jan	74	6.12	18c	34	8	-	33
Feb	"	14.75	24	35	22	86	36
Mar	"	6.69	35	80	93	81	43
Apr	"	27.39	37	80	92	83	43
May	"	31.42		93	98	80	40
Jun	"	48.79		98	99	89	39
Jul	"	31.17		100	100	93	38
Aug	"	33.44		99	99	97	39
Sep	"	34.44		98	93	79	34
Oct	"	14.00		91	97	76	41
Nov	"	11.55		43	77	71	29
Dec	"	5.35		25	55	70	27

Table 1. Evaporation reduction efficiency of floating covers on 9-ft-diameter stock tanks at Granite Reef (continued).

Date Mo Yr	Evaporation from open tank in centimeters	Evaporation Reduction Efficiency of Covers in Percent: Continuous wax (120-135)	Continuous wax (120-125)	Continuous wax (120-125)	Foamed Rubber	Foamed wax blocks
Jan 75	9.48		26	36	80	45
Feb "	9.38		75	56	87	33
Mar "	11.21		76	76	82	26
Apr "	18.09		81	83	83	39
May "	36.38		93	93	67	41
Jun "	37.56		97	96	78	48
Jul "	37.91		97	95	78	37
Aug "	26.64		94	85	84	36
Sep "	26.84		95	90	79	36
Oct "	23.78		66	86	73	33
Nov "	12.67		57	77	68	28
Dec "	8.70		55	59	87	57
Jan 76	11.17		28	50	79	17
Feb "	7.50		33	71	80	33
Mar "	-		-	-	-	-
Apr "	-		-	-	-	-
May "	23.64		94	94	-	46
Jun "	48.86		94	92	-	38
Jul "	20.10		96	85	-	37
Jan 77	-		-	-	-	-
Feb "	-		-	-	-	-
Mar "	7.94		32	55	91d	37
Apr "	33.51		56	79	90	38
May "	22.57		82	90	91	41
Jun "	39.04		91	84	89	33
Jul "	36.93		98	96	89	22
Aug "	32.28		98	93	92	54
Sep "	28.52		86	81	89	32
Oct "	22.90		56	69	93	34
Nov "	15.25		5	19	87	7
Dec "	9.65		11	14	93	34

Table 1. Evaporation reduction efficiency of floating covers on 9-ft-diameter stock tanks at Granite Reef (continued).

Date Mo Yr	Evaporation from open tank in centimeters	Evaporation Reduction Efficiency of Covers in Percent: Continuous wax (120-135)	Continuous wax (120-125)	Continuous wax (120-125)	Foamed Rubber	Foamed wax blocks
Jan 78	4.56		9	10	73	32
Feb "	5.92		9	13	83	29
Mar "	11.04		4	54	78	30
Apr "	12.72		1	76	84	36
May "	34.84		9	82	89	32
Jun "	46.01		66	92	88	29
Jul "	20.18		89	87	95	36
Aug "	17.94		86	70	85	38
Sep "	26.86		77	58	88	32
Oct "	20.54		46	35	85	31
Nov "	6.51		16	18	56	26
Dec "	2.79		0	7	63	10
Jan 79	2.63		0	22	49	22
Feb "	8.25		14	9	90	17
Mar "	6.75		11	15	86	25
Total Evaporation from Open Tank (cm)		878	1868	1531	1012	2118
Total Evaporation from Tank with Cover (cm)		270	376	303	158	1353
Water Saved (cm)		608	1492	1228	854	765
Average Efficiency (%)		69	80	80	84	36
Total Days Exposure (days)		1170	2580	2190	1470	2910

Table 1. Evaporation reduction efficiency of floating covers on 9-ft-diameter stock tanks at Granite Reef (continued).

Footnotes:

a - 92 wax blocks (130°-134° melting point) were placed on the tank. Coverage was estimated to be 70%.

b - 31 wax blocks (120° melting point) were added to complete coverage.

c - Tank allowed to go dry. No additional water was added after 11 January 1974.

d - Foamed rubber cover was placed on a different tank.

Table 2. Cost of cover materials and cost per 1000 gallons of the water saved by the covers.

Cover Material	Purchase Date (yr)	Pounds of Wax (#)	Cost of Cover ($) 1/	Water Saved (cm)	Water Saved (gallons)	Cost per 1000 Gallons Saved ($/1000 gal)
Continuous Wax (120-135)	1970	99	10	608	9,500	1.05
Foamed Rubber	1974	-	16	854	13,300	1.20
Continuous Wax (120-125)	1970	83	8	1,492	23,300	.34
Melted Wax (120-125)	1971	40	5	1,228	19,200	.26
Foamed Wax Blocks	1968	70	7	765	11,900	.59

1/ Cost at time of purchase.

TITLE: CHEMICAL MODIFICATION OF SOILS FOR HARVESTING PRECIPITATION

NRP: 20810 CRIS WORK UNIT: 5510-20810-002

INTRODUCTION:

As in 1978, research on modification of soils to increase precipitation runoff involved both laboratory and field studies. The laboratory studies were designed to evaluate the interfacial relationships of soils treated chemically to stabilize them against erosion, and/or to reduce their surface energy to increase runoff efficiency. Field studies were designed to either test treatments deemed worthy by the laboratory studies, or were part of the runoff farming studies covered elsewhere in this annual report.

The overall objectives of these studies were to:

(1) increase runoff efficiency;

(2) reduce the amount of chemicals required;

(3) increase treatment weatherability (lengthen longevity);

(4) use less costly materials;

(5) increase the range of treatable soils;

(6) increase the climatic range; and

(7) reduce the level of technology required for installation.

LABORATORY STUDIES

Candelilla/Petroleum Wax Mixtures

Candelilla wax is a surplus agricultural commodity in Mexico where it is produced. Water, however, is in short supply in this semi-arid area. The objective of this limited laboratory study was to determine if candelilla or candelilla/petroleum wax mixtures might be useful for treating soils for water harvesting.

Two soils (Granite Reef and Pachappa) were treated in the normal manner: 150 g soil per 65 cm^2 petri dish; wet and compact; air dry; coat with wax. Wax combinations and rates are listed in Table 1.

Samples were first given the 4-hour hydration test to evaluate water repellency and resistance to hydration damage, and were then brushed with a stiff brush to evaluate structural stability. One set of identically prepared samples then was alternately weathered in the freeze-thaw chamber (approximately 8 cycles per day) and eroded under the dripolator (2000, 5-mm drops falling onto the samples from a 2-m height in 5 minutes), while the other set was alternately weathered in a 100% relative humidity chamber and eroded under the dripolator. The process was repeated until the samples eroded through the water repellent layer of soil, or until 300 minutes of dripolator time had been logged (60 times and approximately 500 freeze-thaw cycles). Cracking of samples was noted also.

Sample survival times under the dripolator are listed in Table 1. What constitutes an adequate survival time is a bit arbitrary, but 100 minutes under the dripolator is quite long considering that untreated soil samples will erode through to the bottom of the petri dish in a matter of only a few seconds.

Several conclusions can be drawn from the data:

(1) The mixtures generally survived longer than any of the three waxes alone.

(2) For the Pachappa soil, the low application rate of the C/P mixtures (0.5 kg/m^2) would constitute an adequate treatment (> 100 minutes under dripolator).

(3) For the Granite Reef soil, the 1 kg/m^2 of the C/P mixtures would constitute an adequate treatment provided there was little freeze-thaw cycling at the water harvesting site.

(4) Results for the C/140 mixtures were inconclusive, but the C/140 ratio of 25/75 holds promise.

(5) Cracking was a problem with the Granite Reef soil but not with the Pachappa.

(6) Candelilla wax thus holds promise for treating water-harvesting catchments on some soils.

Stabilizer-Antistrip-Repellent Studies

Preliminary laboratory studies on the development of water repellent water harvesting soil treatments indicated promise for addition of a soil stabilizers and an antistripping agent to wax treatments (1978 Annual Report). These studies were expanded in 1979. Sample preparation and testing for the study reported here were similar to those used previously: 150 g of air dried, < 2-mm soil was placed in 65 cm^2 petri dishes; wetted; packed; air dried; and treated with stabilizer and/or repellent. Two identical sets were prepared.

The testing was to start with the 4-hour hydration test and the 5-minute dripolator test to test for initial repellency and resistance to swelling and shrinking. Then one set was weathered in the freeze-thaw chamber (7 to 9 cycles per day) and the other set in the hydration chamber (100% relative humidity for 24 hours); both sets were then given the dripolator test and the 4-hour hydration test and then recycled in their respective freeze-thaw or hydration chamber. This weathering-testing sequence was continued until the sample failed one of the two tests or else survived 200 minutes under the dripolator (40 sequences for both sets of samples and approximately 350 freeze-thaw cycles for the one set). All samples had 2 to 3 cm diameter water drops placed on their surfaces while weathering. Samples could fail either of the two tests, but since both relate to erosion of the treated layer, results are reported only in terms of minutes of survival under the dripolator. Based on climatic data for the southwest, it was reasoned that 100 minutes under the dripolators should simulate an adequate weathering period in the field. However, weathering was continued until 200 minutes of erosion time had accumulated.

Treatment variables were (1) soil type; (2) stabilizer concentration; (3) repellent (type and rate); (4) antistripping agent; and (5) weathering mode. The soil stabilizer was cellulose xanthate applied at three concentrations (0, 0.2, and 0.5 weight percent paper in water solutions), applied at 1.5 ℓ/m^2 (10 mℓ/petri dish). Six repellents (Table 2) were selected: a paraffin, a slack wax, 3 emulsified waxes, and a silicone. The waxes were applied at 0.25, 0.5, and 1.0 kg wax/m^2, and the silicone at 0.0036 and 0.018 kg silicone/m^2. Two of the waxes (paraffin and slack wax) also were evaluated with 5% Emory 6639 antistripping agent added to the wax. The four soils tested were Superstition sand, Granite Reef sandy loam, Pachappa loam, and Avondale loam.

Results, as expressed in survival time under the dripolator, appear in Table 2. The following discussion is in the reverse order of treatment acceptability: the JN wax emulsion treatment was extremely unpredictable both with respect to wax or stabilizer application rates; it was judged as unacceptable. The 67 paraffin emulsion treatment was marginally acceptable on only the Superstition sand, and then primarily for the hydration weathering mode only. The silicone treatment was adequate for the two coarse textured soils (Granite Reef and Superstition sand) provided both stabilizer and repellent had been applied at the highest rates.

The microcrystalline (M) wax emulsion gave reasonably good protection against both weathering modes for 3 soils at either the 0.5 or 1.0 kg/m^2 rate. The Pachappa soil could even be adequately treated with only 0.25 kg/m^2, provided the soil was previously stabilized. The primary objection with use of the M-wax is its high cost.

Paraffin soil treatments are known to be vulnerable to freeze-thaw cycling, particularly if surface water is present. In this study, only the Pachappa soil showed adequate resistance to such weathering, and that only provided the highest rate of stabilizer had been applied. Three of the soils could be adequately treated if only weathered by hydration, provided the soil was stabilized. Pachappa and Superstition sand could be so treated with only 0.25 kg/m^2 of paraffin.

The paraffin treatment was markedly improved by addition of the antistripping agent. A wax application rate of 0.5 kg was generally adequate for both weathering modes. Little or nothing was gained for two of the soils by stabilizing first with xanthate. This treatment even looked promising for the recalcitrant Avondale soil providing hydration was the only weathering mode. For Pachappa soil, the lowest wax rate (0.25 kg/m^2) sufficed provided the soil was first stabilized.

The 140 slack wax treatment at 0.5 kg/m2 performed adequately with or without separate soil stabilization, on the Granite Reef and Superstition soils provided there was only hydration weathering (even 0.25 kg/m^2 sufficed for the Pachappa soil). Again, little was gained by the xanthate stabilization.

Adding antistrip to the 140 treatment improved resistance to freeze-thaw cycling. Generally, xanthate stabilization improved reliability. Only 0.25 kg wax/m^2 sufficed for the Pachappa soil. Clearly, the treatment combination of 0.2% cellulose xanthate stabilizer, 140 slack wax (containing 5% antistrip) applied at 1/2 kg/m^2 was the most acceptable of all the treatments tested: it met and generally far exceeded the 100-minute minimum under the dripolator for both weathering modes for all four soils.

Cracking problems with this treatment were minimal, also. The 140 slack wax is the least costly of all the repellents tested.

FIELD STUDIES

Granite Reef

Several new treatments were installed at the Granite Reef test site during 1979 (Table 3). Four involved various combinations of cellulose-xanthate stabilizer, an antistripping agent, and either slack wax or paraffin applied at a low rate (0.5 kg/m^2). Paraffin also was applied atop the concrete apron (4-5) to improve runoff efficiency, but the wax did not adequately melt and adhere; retreatment will be attempted in 1980.

Runoff efficiencies for all plots at the site are listed in Table 4. A running list of efficiencies by year for all wax plots is shown in Table 5. The two original paraffin plots are still yielding 76 and 89 percent runoff respectively after eight years.

SUMMARY AND CONCLUSIONS:

Natural plant or animal lipids may be useful for creating water-repellent water harvesting catchments. In many countries these materials are more available and less costly than their petroleum counterparts. A laboratory study showed that soils treated with candelilla/petroleum wax mixtures could be more resistant to weathering than when treated with either wax alone.

Effects of cellulose xanthate soil stabilizer on the weatherability of repellent treated soils were evaluated in the laboratory. Results showed that 1.5 ℓ/m^2 of 0.5 net percent xanthate sprayed on soil surfaces improved weatherability for some repellents, particularly on non-swelling soils. Weatherability (particularly against freeze-thaw damage) of wax treated soils was markedly improved by the addition of 5% by weight of an antistripping agent. Previously wax treatments seemed limited to soils containing less than 25% clay plus fine silt. The new treatment worked successfully in the laboratory on a soil containing 70% clay plus silt.

Several experimental wax plus additives water-harvesting catchments were installed at field sites to evaluate the most promising water-repellent treatments screened from laboratory studies. Material costs for the treatments were less than 10¢/m^2. Laboratory studies suggest a possible 10-year survival with average runoff efficiency exceeding 85%. Water costs, attributable to the materials thus would be only 7¢/1000 gallons in a 24-inch rainfall area or 18¢ in a 10-inch area ($23 and $60 acre foot, respectively).

Personnel: Dwayne H. Fink

Table 1. Resistance of candelilla/paraffin (c/p) and candelilla/140 slack wax (C/140) mixtures to weathering by freeze-thaw cycling and continuous hydration.

		Survival time under dripolator					
		Freeze-thaw			Hydration		
		Wax application rate (kg/m^2)					
Soil	c/p	0.5	1.0	2.0	0.5	1.0	2.0
		min					
Pachappa	100/0	75*	300	300	10	300	300
	50/50	300	300	300*	300	300	300*
	25/75	300	300	300	300	300	300
	0/100	30	40	–	125	175	–
Granite Reef	100/0	0	9*	13*	0	10*	64*
	50/50	20	70	119*	92*	300*	300*
	25/75	53	94	139*	70*	262*	300*
	0/100	20*	24*	50	50	300	300
Granite Reef	C/140						
	100/0	0	9*	13*	0	10*	64*
	50/50	–	10	–	–	10*	–
	25/75	–	145	–	–	300*	–
	0/100	23	0	41	0	300	300

* Cracked during testing.

Table 2. Resistance of repellent-treated soils to weathering by freeze-thaw cycling and continuous hydration.

Soil Treatment			Soil and Weathering Mode							
Stabilizer	Repellent/antistrip		Granite Reef		Sup. Sand		Pachappa		Avondale	
%	Type	Rate kg/m^2	FT	HYD	FT	HYD	FT	HYD	FT	HYD
			min under dripolator							
0	(A); Paraffin 128-131 AMP	0.25	2	5*	1	1	15	25	5*	3*
		0.5	15	15*	19	15	30	125*	5*	5*
		1.0	20*	45*	30*	200	40	175*	5*	5*
0.2		0.25	20	10	22	10	40	55	10*	20*
		0.5	40	200*	45	60	40	200*	10*	20*
		1.0	51*	200*	80	200	50	200	10*	40*
0.5		0.25	25	45*	20	200	85	200	7*	20*
		0.5	35	200*	80	200	120	200	8*	30*
		1.0	41*	200*	135	200	200*	200	10*	35*
0	(B); A + 5% antistrip	0.25	3	25	7	6	200	200	0	0
		0.5	200	200	200	200	200	50	50	135*
		1.0	200	200	200	200	55	200	12	135*
0.2		0.25	40	5	17	35	200*	175	10*	8*
		0.5	200*	40*	200	200	200	200	30	200
		1.0	200	200	200	200	200	200	45	40*
0.5		0.25	75*	25	25	10	200	170	12	40
		0.5	200	200*	200	200	200	200	25*	45*
		1.0	200	200*	200	200	200	90	13	45*
0	(C); 140 slack wax	0.25	7	6	6	10	110	200	0	13*
		0.5	27	200	10	200	195	200	10*	35*
		1.0	30	200	35	200	45	200	10*	40*

* Samples which cracked during testing.

Table 2. Resistance of repellent-treated soils to weathering by freeze-thaw cycling and continuous hydration (continued).

Soil Treatment			Soil and Weathering Mode							
Stabilizer	Repellent/antistrip		Granite Reef		Sup. Sand		Pachappa		Avondale	
%	Type	Rate kg/m^2	FT	HYD	FT	HYD	FT	HYD	FT	HYD
			min under dripolator							
0.2		0.25	35	10	10	200	200	200	10	55*
		0.5	42	200	45	200	200	200	12*	30*
		1.0	60	200	135	200	200	200	12	50
0.5		0.25	30	75*	8	200	200	200	8*	45*
		0.5	42*	140	45	200	200	55	8*	10
		1.0	62	200*	155	200	200	200	13*	50
0	(D); C + 5% antistrip	0.25	8	7	0	0	50	200	13	0
		0.5	200	200	200	15	50	200	28	45
		1.0	200	200	100	200	200	200	200	200
0.2		0.25	10	75*	8	7	200	200	30	70*
		0.5	200	200	200	200	200	200	200	95
		1.0	200	200*	200	200	200	200	200*	200
0.5		0.25	80	95*	10	85	200	200	22	55*
		0.5	200	200	200	200	200	55	25	55*
		1.0	200	200	200	200	200	200	200	200*
0	(E); M-micro-crystalline (emulsion)	0.25	3	0	6	3	50	85	0	11*
		0.5	120	30*	190	200	50	175	13	55
		1.0	190*	200*	200	165	200	50	20	40*
0.2		0.25	25	200	2	10	200	165*	7	8*
		0.5	200	125*	200	200	200	175	12	55*
		1.0	190*	95*	200	185	200	75*	25*	45*

Table 2. Resistance of repellent-treated soils to weathering by freeze-thaw cycling and continuous hydration (continued).

Soil Treatment			Soil and Weathering Mode							
Stabilizer	Repellent/antistrip		Granite Reef		Sup. Sand		Pachappa		Avondale	
%	Type	Rate kg/m^2	FT	HYD	FT	HYD	FT	HYD	FT	HYD
			min under dripolator							
0.5		0.25	10	9	9	95	110	175	13	55
		0.5	200	200	200	200	200	175	20*	45*
		1.0	190*	200*	200	200	180	165*	25*	45*
0	(F); 67-paraffin (emulsion)	0.25	3	4	3	1	15	45	0	0
		0.5	15	30	27	200	40	55	8*	5*
		1.0	21	10*	28	200	40	200	10*	30*
0.2		0.25	10	9	9	21	30*	200	8*	7*
		0.5	35	45*	88	200	90	200	7*	5*
		1.0	63*	90*	200	200	40	200	8*	40*
0.5		0.25	10	10	12	30	165	55	10*	13*
		0.5	50*	40	50	200	50	60	10*	13*
		1.0	62	200	200	200	40	55	8*	40*
0	(G); JN-paraffin, microcrystalline wax mixture (emulsion)	0.25	0	0	1	1	40	55	0	3*
		0.5	20	35	85	200	45	200	10*	8*
		1.0	40*	200*	0	0	45	200	8*	5*
0.2		0.25	0	0	6	4	75	170	8	3
		0.5	45*	150*	200	200	55	55	16	13
		1.0	82*	155*	0	0	40	200	12*	35*
0.5		0.25	0	0	8	8	50	175	10*	20
		0.5	40*	20	200	200	200	200	17	40*
		1.0	69*	200*	0	0	200	55	20*	35*

hydration (continued).

Soil Treatment			Soil and Weathering Mode							
Stabilizer	Repellent/antistrip		Granite Reef		Sup. Sand		Pachappa		Avondale	
%	Type	Rate kg/m2	FT	HYD	FT	HYD	FT	HYD	FT	HYD
			min under dripolator							
0	(H); 772-silicone	a	2	2	2	1	3	3	5	3
		b	21	27	3	1	35	35	12	20
0.2		a	4	3	4	8	12	30	10	8*
		b	98	110	8	54	35	35	10	45*
0.5		a	29	50	0	0	50	75	12	45
		b	85	200	140	185	50	35	25*	45

Table 3. Treatment changes at Granite Reef during 1979.

Plot	Date	Treatment
T-3	21 June	Chevron 140 slack wax containing 5% by wt of Trymeen 6639 antistrip, applied at 0.4 kg/m^2 to compacted soil.
T-4	21 June	Chevron 140 slack wax containing 5% Trymeen 6639 antistrip, applied at 0.4 kg/m^2 to compacted and stabilized (0.5% cellulose xanthate solution, applied at 1.6 ℓ/m^2) soil.
T-15	10 July	Scale paraffin (128-131 AMP) containing 5% Emery 6639 antistrip, applied at 0.5 kg/m^2 to rain-compacted and stabilized (0.25% cellulose xanthate solution applied at 3.2 ℓ/m^2) soil.
T-12	17 July	Chevron 140 slack wax containing 5% Trymeen 6639 antistrip, applied at 0.5 kg/m^2 to compacted and stabilized (0.5% cellulose xanthate solution, applied at 3.2 ℓ/m^2) soil.
A-5	24 July	Hand-spread, ground, refined paraffin on concrete surface.
W-3	14 Sept	Restore by chipping off all weeds and brush.

Table 4. Rainfall-runoff from water harvesting plots at Granite Reef in 1979.

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
1979	mm								%								
5 Jan	4.6	96.4	0	24.7	81.7	UN	90.0	51.4	0	60.6	0	25.1	91.2	49.5	0	19.9	36.7
9	1.5	91.3	0	0	80.0	UN	86.7	30.7	0	50.6	0	0	88.9	0	0	0	43.6
16-17	32.8	F	M	68.2	96.6	UN	97.8	80.4	21.8	81.0	16.4	59.2	97.2	78.0	27.4	56.0	85.5
18	12.7	97.2	30.9	75.8	96.6	UN	95.5	79.0	42.1	83.4	36.9	67.9	94.8	79.5	50.0	69.3	89.8
18-19	11.0	94.4	10.1	66.7	97.0	UN	97.0	72.5	23.0	81.0	16.4	61.4	93.8	67.2	31.2	60.5	85.1
21	1.3	91.2	0	6.9	82.7	UN	80.4	44.2	0	44.0	0	28.5	55.6	19.2	0	23.5	58.6
24-25	17.8	99.9	21.7	65.9	98.5	UN	99.1	73.4	29.2	82.2	24.8	59.6	98.5	71.0	37.0	59.9	83.6
28	7.2	93.4	8.5	50.3	94.9	UN	95.5	59.7	12.7	69.3	11.6	17.8	93.9	57.6	24.3	41.7	72.6
1-2 Feb	1.8	100.0	0	0	78.0	UN	95.3	32.5	0	22.2	0	0	100.0	0	0	0	32.4
2 Mar	18.0	100.0	0	25.3	100.0	UN	100.0	76.6	0	69.3	0	22.6	98.8	69.4	0	7.2	83.0
2	1.8	80.0	0	4.4	65.6	UN	79.2	67.5	0	52.1	0	21.1	74.1	32.4	0	8.6	66.7
20	25.3	100.0	34.0	76.9	97.4	UN	100.0	87.5	33.3	87.9	39.0	61.0	97.7	81.1	40.8	51.0	84.0
28	27.9	97.5	4.2	61.7	98.8	UN	99.8	85.8	8.8	77.4	8.1	45.9	96.0	73.9	16.0	49.6	81.7
16-20 May	16.5	100.0	0.8	43.8	39.2	UN	100.0	M	4.7	76.8	1.7	35.5	99.6	63.4	18.1	36.5	72.7
25	10.0	100.0	0	33.8	96.1	UN	100.0	M	7.1	69.9	2.8	24.5	100.0	50.3	6.4	34.9	66.3
17 Jul	1.8	52.2	0	0	M	UN	100.0	42.5	0	19.4	0	0	96.0	0	0	0	20.9
11-12 Aug	19.8	74.2	12.6	23.7	76.5	UN	91.9	73.2	27.4	69.7	19.3	38.6	87.0	49.4	22.8	35.2	64.8*
20 Oct	23.1	100.0	M	M	83.2	UN	100.0	93.9	49.6	92.3	M	70.6	95.5	M	M	M	M
8 Nov	4.8	99.4	0	0	54.3	UN	93.5	38.5	0	36.5	0	0	93.3	M	0	0	81.4
20-21 Dec	2.3	72.4	0	0	M	UN	M	23.7	0	3.1	0	0	M	0	0	0	75.2
Totals**	242.0	95.4	11.8	51.4	88.6	UN	97.7	76.7	20.8	76.2	15.4	46.2	95.6	66.3	22.8	42.7	79.0 68.6

Notation: F = overflowed storage; M = mechanical malfunction; UN = untreated; ∔ = accumulated rainfall events;
* = initiation of new treatments, or maintenance of catchment.
** Percentage totals are based on measured data only, i.e., no estimates.

Table 4. Rainfall-runoff from water harvesting plots at Granite Reef in 1979 (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
1979	mm								%										
5 Jan	4.6	0	0	0	86.1	73.9	UN	UN	80.4	30.4	69.6	56.5	93.4	8.7	91.3	UN	69.6	10.9	UN
9	1.5	0	0	0	not measured →														
16-17	32.8	M	17.6	22.9	F	100.0	UN	UN	100.0	78.6	92.9	60.9	F	56.4	F	UN	92.7	39.0	UN
18	12.7	M	27.0	35.2	M →														
18-19	11.0	M	15.1	20.0	M →														
21	1.3	M	0	0	M →														
24-25	17.8	M	16.8	28.0	M →														
28	7.2	M	8.2	18.8	M →														
1-2 Feb	1.8	M	0	0	72.0	0	UN	UN	55.5	0	0	50.0	100.0	0	88.9	UN	0	0	UN
2 Mar	18.0	↓	↓	↓	↓	↓	UN	UN	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	UN
2	1.8	7.6	7.8	M	M	M	UN	UN	96.5	32.8	83.8	49.5	100.0	17.7	100.0	UN	89.9	5.0	UN
20	25.3	33.9	27.0	M	100.0	57.3	UN	UN	100.0	62.0	97.2	69.2	100.0	65.2	100.0	UN	M	38.7	UN
28	27.9	9.8	9.4	11.2	100.0	86.0	UN	UN	100.0	51.6	100.0	65.2	100.0	46.6	100.0	UN	99.3	19.3	UN
16, 20 May	16.5	3.8	0	1.6	90.3	70.3	UN	UN	82.4	38.8	81.2	52.1	96.4	36.9	94.6	UN	79.4	13.3	UN
25	10.0	0	0	0	NP →														
17 Jul	1.8	0	0	0	NP →														
11-12 Aug	19.8	15.1	7.4	17.0	100.0	78.3	69.2*	85.8*	M	M	M	M	M	M	100.0	89.4*	100.0	34.3	87.8*
20 Oct	23.1	56.3	45.7*	61.5	100.0	93.0	M	100.0	M	M	M	62.2	M	84.8	100.0	100.0	M	82.3	100.0
8 Nov	4.8	0	0	0	100.0	54.2	41.7	43.8	100.0	0	43.8	14.6	93.8	0	95.8	81.2	54.2	0	70.8
20-21 Dec	2.3	0	0	0	95.6	34.8	52.2	52.2	34.8	0	65.2	0	95.6	0	100.0	87.0	43.5	0	52.2
Totals**	242.0	18.7	12.7 45.7	21.1	97.7	79.7	62.8	86.8	95.0	51.7	88.2	58.3	98.7	48.8	98.8	93.4	88.7	32.2	90.2

Table 5. Summary of runoff efficiencies from wax-treated plots at Granite Reef.

Year	Precip. mm	R-2	T-13	T-6	T-7	T-3	T-4	T-12	T-15	A-5
		Wax-Treated Plots 1/								
		% runoff								
1972	244	90	92							
1973	208	87	88							
1974	251	85	2/	75						
1975	183	88	96	76						
1976	193	86	91	73						
1977	116	70	77	53						
1978	540	81	88	62	83					
1979	242	76	89	52	88	63	87	93	90	69

1/ First year's data represents partial year.

2/ Missing data.

TITLE: RAINFALL, RUNOFF, AND EROSION RELATIONSHIPS FROM AGRICULTURAL WATERSHEDS IN HAWAII

NRP: 20810 CRIS WORK UNIT: 5510-20810-003-A

INTRODUCTION:

The Hawaiian rainfall-runoff-erosion project conducted on six small agricultural watersheds in cooperation with the University of Hawaii, was terminated in July 1979. All of the almost eight years of data have been processed and stored on disk cartridges for further use. A report that presents the data collected through 1977, and summarizing the results obtained, has been submitted to the Western Region for publication as a SEA-ARM Series publication. This report will be updated using the 1978 and 1979 data when analysis is completed. Several other reports dealing with specific portions of the study have been published as journal articles, or are in press. Preliminary results indicate that both sugarcane and pineapple provide more protection than anticipated, thus observed runoff and erosion are less than that estimated by present models.

PROCEDURE:

Rainfall and runoff data from the six small agricultural watersheds were collected on strip charts and processed into engineering units on digitizers and computer facilities at the U. S. Water Conservation Laboratory. Sediment and erosion data are collected and processed by soil technicians from the University of Hawaii. All data are then stored on disk cartridges for computer analysis.

RESULTS AND DISCUSSION:

A brief summary of events occurring and conditions observed during the six-month study period in 1979 follow:

1. Laupahoehoe - A complete cover of sugarcane over 10 feet high covered this watershed until it was harvested on June 5, 1979. Although the cane was then ratooned, the watershed was essentially bare the last month of the study.

2. Honokaa - This site also had a complete cover of over 10-foot high sugarcane until it was harvested on May 5, 1979. It too was ratooned, but was essentially bare when equipment was removed on July 6, 1979.

3. Waialua Sugar - A complete cover of sugarcane had developed on this site by January 1979 and continued until the study was terminated.

4. Mililani - A mature pineapple crop over 3 feet high provided a complete cover on this watershed during the six-month study period.

5. Kunia - A complete cover of pineapple also covered this site throughout the 1979 study period.

6. Helemano - This trickle-irrigated site had a complete cover of sugarcane during the 1979 study period. Unfortunately, grading of the road in front of the measuring flume destroyed the watershed boundary allowing runoff to bypass the flume.

Analysis of the data through 1977 has been completed, and indicates that observed runoff and erosion are less than present models predict. SCS runoff curve number tables are being revised, based on these results. Factors in the Universal Soil Loss Equation will also be adjusted using erosion data obtained in this study, in an effort to reduce estimates of erosion presently obtained using this model.

Although observed sediment losses were less than presently accepted allowable sediment loss limits for all six watersheds, the watersheds with a significant portion of the area in roads approached this limit. More emphasis on proper installation and maintenance of conservation measures on these field roads could therefore reduce sediment losses significantly. On sugarcane fields where roads are seldom a major problem, sediment losses could be reduced by scheduling harvests for erosion prone areas to coincide with climatic periods when erosive storms are less likely to occur.

SUMMARY AND CONCLUSIONS:

The Hawaiian rainfall-runoff-erosion project conducted on six small agricultural watersheds in cooperation with the University of Hawaii was terminated in July 1979. All of the almost eight years of data have been processed and stored on the computer for further use.

A brief summary of cover conditions on the watersheds for the six months of operation in 1979 follows: (1) two of the sugarcane watersheds had a complete cover until harvested in late spring, (2) the other two sugarcane watersheds had a complete cover during the six-month study period, and (3) the two pineapple watersheds had a complete crop cover during the study period.

A report presenting rainfall-runoff-erosion, and other data for the period 1972-1977, along with a summary of results, has been submitted to Western Region for publication. Results to date indicate that both sugarcane and pineapple provide more protection than originally anticipated. Thus, observed runoff and erosion are less than that predicted by present models. SCS runoff curve number tables are being revised based on these findings. Factors in the erosion models will also be modified to reduce erosion estimates.

Sediment losses from some sugarcane areas could be reduced by scheduling harvests of erosion prone fields to coincide with low erosive potential climatic periods. Proper installation and maintenance of conservation measures on field roads could reduce erosion losses from pineapple fields without changing present farming practices.

PERSONNEL: Keith R. Cooley

APPENDIX

LIST OF PUBLICATIONS

AND MANUSCRIPTS PREPARED IN 1979

MS No.

NRP 20740 IMPROVE IRRIGATION AND DRAINAGE OF AGRICULTURAL LAND

Published:

Bucks, D. A., Nakayama, F. S. and Gilbert, R. G. Trickle irrigation water quality and preventive maintenance. Agri. Water Management 2(2):149-162. June 1979. 669

Bucks, D. A. Trickle irrigation: Promises and problems. California-Arizona Farm Press. pp. 36, 41. Oct. 1979. 754

Clemmens, A. J. Control of modified demand irrigation distribution systems. Proc. Am. Soc. of Civ. Engin., Irrig. and Drain. Div. Specialty Conference, Albuquerque, NM, July 1979. Irrigation and Drainage in the Nineteen-Eighties, pp. 303-313. 718

Clemmens, A. J., and Strelkoff, Theodor. Dimensionless advance for level-basin irrigation. Jour. Irrig. and Drain. Div. 105(IR3):259-273. Sept. 1979. 674

Dedrick, A. R. Automated gates to level basins show improvements. California-Arizona Farm Press p. 20. Oct. 27, 1979. 722

Erie, L. J. and Dedrick, A. R. Level basin irrigation: A method for conserving water and labor. USDA Farmers' Bulletin No. 2261. 1979. 646

Erie, L. J. and Dedrick, A. R. Level basin irrigation leads to higher yields. California-Arizona Farm Press. p. 16. Oct. 1979. 757

Gilbert, R. G., Nakayama, F. S., and Bucks, D. A. Trickle irrigation: Prevention of clogging. Trans. Am. Soc. Agric. Engin., 22(3):514-519, 1979. 645

Nakayama, F. S., Bucks, D. A., and Clemmens, A. J. Assessing trickle emitter application uniformity. Trans. Amer. Soc. Agric. Engin. 22(4):816-821. 1979. 659

Published: Replogle, J. A. and Fangmeier, D. D. Conserving water and energy in irrigation. In Proc. Symp. on Water Conservation Alternatives for Groundwater and Surface Water Utilization. Amer. Water Resources Assoc., Phoenix, Az. April 12, 1979. pp. 18-35. 1979. 760

Replogle, J. A. Irrigation flow measurement simplified. California-Arizona Farm Press. pp. 24-25. Nov. 3, 1979. 755

Prepared: Clemmens, Albert J., and Replogle, J. A. Constructing simple measuring flumes for irrigation canals. USDA Farmers Bulletin No. 2268. 1979. (In Press) 695

Clemmens. A. J. Depths of flow in level basins. Trans. of the Amer. Soc. Agric. Engin. (In Press) 715

Nakayama, F. S. and Bucks, D. A. Clogging effects on emitter discharge rate and trickle irrigation uniformity. Trans. Amer. Soc. Agric. Engin. (Submitted for publication) 733

Replogle, J. A., and Clemmens, A. J. Broad-crested weirs for portable flow metering. Trans. Amer. Soc. Agric. Engin. (In Press) 681

Replogle, J. A., Merriam, J. L., Swarner, L. R, and Phelan, J. T. Farm water delivery system. Chapter 9, ASAE Monograph "Design and Operation of Farm Irrigation Systems." (In Press) 712

Replogle, J. A., and Clemmens, A. J. Measuring flumes of simplified construction. Trans. of Amer. Soc. Agric. Engin. (In Press) 736

NRP 20760 MANAGEMENT AND USE OF PRECIPITATION AND SOLAR ENERGY FOR CROP PRODUCTION MS No.

Published: Brazel, A. J. and Idso, S. B. Thermal effects of dust on climate. Annals Assoc. Amer. Geogr. 69:432-437. 1979. 676

Davies, J. A. and Idso, S. B. Estimating the surface radiation balance and its components. Chap 3.3. "Modification of the Aerial Environment of Plants." In Amer. Soc.

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Idso, S. B. Infrared extinction and the mass concentration of atmospheric aerosols. Atmos. Environ. 13:1725-1729. 1979. 710

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Jackson, R. D., Pinter, P. J., Jr., Idso, S. B., and Reginato, R. J. Wheat spectral reflectance: Interaction between crop configuration, sun elevation, and azimuth angle. Applied Optics. 18(22):3730-3732. Nov. 1979. 730

Kimball, B. A., and Mitchell, S. T. Tomato yields from CO_2-enriched, unventilated and conventionally ventilated greenhouses. Jour. Amer. Soc. Hort. Sci. 104(4):515-520. 1979. 698

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Pinter, P. J., Jr., and Butler, G. D., Jr. Influence of cotton irrigation frequency on the duration of the prepupal and pupal stages of non-diapausing pink bollworms. Environ. Entomol. 8:123-126. 1979. 658

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