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EFFECTS OF IRRIGATION METHODS ON GROUNDWATER POLLUTION BY NITRATES AND OTHER SOLUTES

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ABSTRACT

Sprinkler irrigation, furrow irrigation, subirrigation, automated subirrigation, criteria for applying irrigation water, methods of applying fertilizer and sources of fertilizer were investigated as to their potential to decrease possible pollution from nitrate and other solutes in a loamy fine sand soil overlying a shallow aquifer in Knox County, Texas.

Less nitrate-nitrogen was available for leaching in subirrigation systems than furrow and sprinkler systems. Less irrigation water was applied with automated subirrigation systems than with the other irrigation systems. However, crop water requirement was not significantly changed--the soil water was more efficiently used. Fertilizer remained in the root zone if the water applied was based on potential evapotranspiration and leaf area regardless of the irrigation system or the criteria used to apply the irrigation water. Banded fertilizers moved differently in the different irrigation systems.

Subirrigation has the possibility of having irrigation return flow with lower concentrations of other solutes than sprinkler or furrow systems.

Banding fertilizer in the bed was superior to banding below the level of the water furrow and applications in the irrigation water relative to quality of irrigation return flow. No one source of nitrogen fertilizer was indicated to be superior.

Current fertilization practices are not causing major increases in the nitrate-nitrogen level in the aquifer.

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The study was supported by the U. S. Environmental Protection Agency under Programs 13030EZM and S802806, Dr. J. P. Law, Project Officer; by The Texas Agricultural Experiment Station at two locations: Texas A&M University Vegetable Research Center at Munday, Texas, Dr. M. C. Fuqua, Director; and Texas A&M University Agricultural Research and Extension Center at Lubbock, Texas, Dr. George G. McBee and Dr. Bill Ott, Resident Directors of Research; and by the Texas Water Resources Institute, Dr. J. R. Runkles, Director.

SECTION 1

INTRODUCTION

Irrigated agriculture is the major consumer of water in the western United States. With the increasing demand for water for municipal and industrial needs, there is increasing concern about the influence of irrigated agriculture on the quality of the nation's water resources. Water applied in irrigated agriculture may evaporate from the soil or crop surface or leave the area of application as runoff or leachate. The water leaving the area of application may be degraded due to a high concentration of mineral salts from soil water evaporation and plant transpiration. Law (15) notes in his summary that 20-fold increases in mineral content have been noted in the Colorado and Rio Grande Rivers due to the low quality of irrigation return flows.

Intensification of crop production has resulted in increased applications of nitrogen fertilizer. In many cases, the amount of fertilizer applied is in excess of that required by the crop. This excess, along with nitrate available from nitrification, may be leached from the root zone if water is applied in excess of that required by the crop. Water containing greater than 45-ppm nitrate or 10-ppm nitrogen as nitrate is considered a hazard to animal life by causing methemoglobinemia (4,16).

Many irrigated areas have geological and soil characteristics which favor water losses through irrigation return flows that are of poor quality. These areas include the Platte River Valley in Nebraska, the Helena Valley in Montana and the San Luis Valley in Colorado, as well as the Colorado River Valley previously mentioned.

Another such area is the Seymour water-bearing formation in Texas (19). The formation underlays 1120 sq km in Knox and Haskell Counties in the Rolling Plains of Texas. Groundwater in the formation is derived solely from precipitation (25 to 102 cm per year) on the outcrop within the two counties. Prior to 1900 the Seymour formation was nearly dry. It was filled with water between 1900 and 1935 when the rainfall was generally above normal, and a large part of the land was cleared of its native grass vegetation and placed in cultivation. The water level in one well in this formation rose 18.4 m during this 35-year period. A majority of the wells are drilled to a depth of only 9.1 to 21.3 m. The static water level varies from ground level to a depth of 9.1 m. The water table slopes generally 2.4 to 3.0 m per kilometer toward the northeast. Water is discharged into the Brazos River through numerous springs and seeps.

The water in the Seymour formation contains a large amount of nitrate-nitrogen (nitrate-N). The nitrate-N content of 62 samples of groundwater taken from this aquifer in 1962 ranged from 21- to 183-ppm nitrate with 39 exceeding the recommended Department of Health limit of 45 ppm. The cities of Haskell, Rule, Rochester, O'Brien, Knox City, Munday, Goree, Rhineland, and Weinert all use the formation for a water supply and none have an approved water supply. Haskell, Knox City, Munday, and Goree have formed a water district to obtain a surface water supply; however, the Seymour formation is the only source of water for the other small towns and farmsteads of the area.

Initially, the high nitrate-N in the water may have been due to leaching of nitrates from the grassland when it was put in cultivation. Inorganic nitrogen does not accumulate under grassland due to slow rates of mineralization; however, total nitrogen accumulations are highest under grass vegetation. Most of this nitrogen is bound in organic form. When placed under cultivation, organic nitrogen in such soils decreases rapidly due to mineralization. Total nitrogen also decreases due to crop removal and leaching of the inorganic nitrogen. In a sandy soil, nitrates have been shown to move downward 45 cm with a 10-cm application of water (7). Nitrate levels of 200 ppm have been found to accumulate during the breakdown of organic residues.

Since 1951, the area has been changing from a dryland agriculture to an irrigated agriculture. Between 1951 and 1968, the number of irrigation wells increased from 25 to over 2,000 (17). With increasing irrigation, there have also been increases in fertilization. There is some indication that the nitrate-N level of the wells of the area is increasing. According to analyses from the Texas State Department of Health Laboratories, nitrate in the city well of O'Brien rose from 67 to 165 ppm between 1960 and 1965.

There is some question with respect to the contribution of nitrogen fertilization to the above-mentioned increases in nitrate-N in the water table. In 1970, a cooperative project between the Environmental Protection Agency and the Texas Agricultural Experiment Station was approved. In the project, facilities in Knox and Lubbock Counties, Texas, were used to compare current and new irrigation and fertilization methods to determine the following:

a. The contribution of current irrigation and fertilization practices to pollution of underground water.

b. The potential of using modified current irrigation and fertilization practices for immediate reduction of pollution.

c. The potential of using subirrigation for more efficient water application and new systems of fertilization for long-range solutions to the pollution problem.

d. The economics of installation, operation, and maintenance of subirrigation systems as compared to conventional irrigation systems and economics of each fertilization practice.

From data obtained during the first year of the project, it was noted that concentrations in excess of 40-ppm nitrate-N occurred in soil-water extracts from the profiles of unfertilized plots. Therefore, nitrate-N concentrations in the profiles of fertilized plots were a result of both soil nitrogen and nitrogen from fertilizers, and it was difficult to assess separately the contribution of soil nitrogen and fertilizer nitrogen to the nitrate-N at various depths in the soil profile. Since crops use both sources of nitrogen and both sources may be contributors of nitrogen to irrigation return flow, it was necessary to distinguish between the contributions of each source before conclusions concerning the degradation of irrigation return flows by nitrogen fertilizers could be made.

In 1973, the original project was augmented with a supplementary study using nitrogen fertilizer tagged with the nitrogen isotope, ^{15}N, with the following objectives:

a. To determine separately the contributions of soil nitrogen and fertilizer nitrogen to the nitrogen available to irrigation return flow.

b. To determine the influence of different irrigation systems (sprinkler, furrow, and subirrigation) on the distribution of soil nitrogen and fertilizer nitrogen.

Fertilizer enriched with ^{15}N was applied to duplicate plots in the furrow irrigation, sprinkler irrigation, and subirrigation systems during the 1973 growing season.

It was difficult to draw any significant conclusions concerning the behavior of ^{15}N with only one year's data relative to the cycling of crop residue and movement of the fertilizer remaining in the profile after the growing season was completed. Another growing season was needed to obtain this information. Furthermore, analyses during the first three years of the project showed that nitrate and other solutes are moving below the root zone. Another year's data from samples procured below the root zone was needed to further evaluate the movement of the nitrate and other solutes below the root zone into the underground aquifer. Therefore, a continuation of the project was proposed for 1974 with the following objectives:

a. To determine separately the contributions of soil nitrogen and fertilizer nitrogen from both previous and current years' fertilizer application to nitrogen available to irrigation return flow from sprinkler irrigation, furrow irrigation, and subirrigation systems.

b. To determine the influence of rainfall and irrigation water applied through sprinkler irrigation, furrow irrigation, and subirrigation systems on the movement of nitrate-N and other solutes below the root zone following treatment with different rates and sources of nitrogen fertilizer.

The study was conducted in an area on which a minimum of research had been conducted. It was, therefore, necessary to obtain definitive information concerning the chemical and physical properties of the soil and characteristics of the climate as they influence the water available for irrigation return flow. Models used during the course of the study were either those developed by other researchers or statistical in nature. The models used are noted in the various sections of the discussion.

SECTION 2

CONCLUSIONS

1. Less nitrate-N is available to be leached from fertilizer applied to subirrigation systems than sprinkler or furrow irrigation systems.

2. The data indicate that nitrate-N in the immediate zone of the subirrigation pipe is denitrified.

3. More nitrogen fertilizer is recovered in plants when applied to sprinkler systems than the furrow irrigation systems with the lowest recovery occurring from nitrogen applied to subirrigation systems.

4. Only small amounts of fertilizer nitrogen (2 to 7%) are available to the following year's crop in loamy fine sand soils.

5. Fertilizer nitrogen remaining in the soil profile at the beginning of the year following application is primarily in the organic form.

6. Movement of nitrate-N from the root zone was more of a problem between growing seasons than during growing seasons due to rainfall. During the growing season it was usually possible to maintain the nitrogen in the root zone in all irrigation systems by irrigating on the basis of potential evapotranspiration (ET).

7. Banded fertilizers have unique patterns of movement in each of the irrigation systems: In sprinkler systems, the fertilizer moves vertically as discrete bands; in furrow irrigation systems, the bands merge in the bed and move down; in subirrigation systems, the bands move away from the subirrigation system.

8. Due to the uniqueness of movement of the bands in the different irrigation systems, detailed cross sectional soil sampling is preferable to porous bulb extracts.

9. Automatic subirrigation systems are superior to manual subirrigation and sprinkler systems which are superior to furrow irrigation systems in the amount of irrigation water required to produce corn even if the manual systems applications are scheduled based on potential ET.

10. No significant differences in total water requirement of corn were noted between the various irrigation systems. The soil water was used more efficiently when less irrigation water was applied.

11. Supplemental irrigated areas can increase irrigation water-use efficiency significantly by utilizing systems so that a portion of the root zone remains dry for the storage of rainfall.

12. The data indicate that the quality of irrigation return flows of subirrigation systems will be superior to furrow and sprinkler irrigation systems because the concentrations of all solutes and the electrical conductivity (EC) were lower.

13. A zone low in all solutes is formed in the path of water flow around the subirrigation pipe.

14. Soil-water content and soil-water potential varied less in the surface 0.3 m in the subirrigation system than in the furrow and sprinkler irrigation systems.

15. Automated subirrigation systems produce more yield/unit of water but less total yield than the other irrigation systems.

16. The subirrigation systems currently are beset with too many problems and are too expensive to be used for low value crops.

17. There is no difference in quality of irrigation return flow and yield/unit of nitrogen when irrigations at leaf curl, -20 centibars (cb) and -40 cb potential were compared provided the amount added is based on potential ET and crop leaf area. Total yield is higher when the crop is irrigated at -20 cb while yield/unit of water is higher when the other criteria are used.

18. Banding fertilizer in the bed is superior to banding fertilizer below the level of the water furrow or applying it in the irrigation water with respect to nitrate-N in irrigation return flows.

19. No one source of fertilizer was indicated to be better in any way.

20. The soil is too variable to use an analytical model to predict nitrate and/or solute movement.

21. An empirical model shows that the most important factors affecting nitrate-N in the leachate are the amount of irrigation water applied and the nitrate-N in the profile.

22. When irrigation water applied is >2 x potential ET and the nitrate-N is >200 kilograms per hectare (kg/ha), the leachate will have an undesirable concentration of nitrate-N (>20 ppm).

23. Bromide can be used as a tracer to indicate nitrate and water movement.

24. For each cm of water added in excess of evaporation and ET, nitrate moved down 7.4 cm.

25. The variable layered soils are a factor in causing "field capacity" to be -10 cb rather than the accepted value of -33 cb.

26. Up to 50 kg/ha of nitrogen each year are mineralized from the soil of the study area.

27. Since the wells received horizontal recharge, potential pollution of groundwater other than at the site is a possibility.

28. The relationship between the ratio of actual to potential ET and leaf area index (LAI) is approximately the same for sweet corn, cotton and sorghum and probably applies to all crops.

29. Because salts are moved upward from subirrigation emitters, periodic supplemental leaching with another system may be needed in vary arid areas.

30. Current fertilization practices are not expected to cause dramatic increases in nitrogen in the aquifer.

SECTION 3

RECOMMENDATIONS

1. Since subirrigation has the potential of enhancing the quality of irrigation return flows, problems with equipment and plugging should be solved. Even though it is expensive, it has potential use where the disposal of high nitrate water is a problem due to the apparent denitrification that occurs with the system.

2. The significant increases in irrigation water-use efficiency and quality of irrigation return flow suggest that the possibility of automation of current sprinkler and furrow irrigation systems needs to be investigated as a practical alternative to improving the quality of irrigation return flows until automated subirrigation systems become commercially available.

3. If yields could be substantially increased, the cost of automated systems could be offset. Current plant varieties have been developed with current irrigation systems. It is possible that cultivars could be developed which would respond more positively to the ideal soil moisture conditions which are available with automated irrigation systems.

4. If irrigation applications are based on a combination of potential ET and leaf area development, and only the amount of nitrogen required by the crop is applied, nitrate-N in irrigation return flows will be minimal.

5. The growth of longer season crops or double cropping is a possibility for maintaining nitrate-N in the root zone if water is adequate for crop growth.

6. In supplemental irrigated areas, modification of current furrow and sprinkler irrigation systems so that a dry area exists in the root zone for storage of rainfall would substantially increase irrigation water-use efficiency.

7. Banding fertilizer in the bed rather than below the level of the water furrow could be immediately initiated to enhance quality of irrigation return flows.

8. The low potential (-10 cb) at "field capacity" due to layering is probably a characteristic of many soils. This creates high water-holding capacity which is an aid in maintaining quality of

irrigation return flows. A survey of the soils of the U. S. to see where such characteristics are present would be an aid in developing management recommendations.

9. A summary of the nitrogen mineralization capability of various soils would be an aid in modeling and making management decisions relative to fertilization with nitrogen.

10. Although current fertilization practices are not contributing to the nitrate-N of the aquifer in the area studied, the possibility exists if the area were to produce a large acreage of shallow-rooted vegetable crops which are fertilized heavily and irrigated frequently with inefficient furrow irrigation systems. Due to the horizontal movement of water in the aquifer, contamination could easily occur from locations outside the area of the wells.

11. Due to surface recharge from excess rainfall, the area has the potential of having a perpetual water supply. A system of monitoring the quality of current wells and regulating the number of new wells would aid in maintaining the quality and quantity of the water in the aquifer indefinitely.

SECTION 4

MATERIALS AND METHODS

MUNDAY LOCATION

Field Site Development

Site Selection--

For this study it was necessary to locate a uniform site of a typical soil series which had not been irrigated or fertilized. The Miles series is a loamy sand to fine sandy loam soil (Udic Paleustalfs) common to a large area of Texas and Oklahoma. However, there was some difficulty in locating a uniform site of the series because many of the potential sites had 0.2 to 0.4-hectare (ha) areas with a clay lens (>40% clay) at 0.91 to 1.22 m with the remainder of the sites being typical of the Miles series. A 10.13-ha site suitable for the study was obtained on the Earl Claburn Farm located 11.3 km west and 2.5 km north of Munday, Texas. A three-year lease was obtained with the option to renew as long as the Texas Agricultural Experiment Station used the site for research.

Five test holes were drilled on the site to determine the strata below the surface and the extent of water-bearing formations. The logs of the test holes showed that the water-bearing formations began at 7.6 to 10.6 m below the surface and continued to 13.7 to 16.7 m.

Analyses of the clay fractions were performed by Dr. Joe Dixon, Professor of Mineralogy, Texas A&M University. Clay fractions from Miles soil and underlying sediments to 9.1 m were surveyed for mineral content by x-ray diffraction procedures. Montmorillonite and mica (illite) were the major components. Montmorillonite and mica occurred as discrete minerals and in complex interstratified mixtures typical of soils of the region. Kaolinite and vermiculite were identified in small amounts. Chlorite occurred sporadically in small amounts. Quartz was present in appreciable amounts in all clays, and feldspar occurred in small amounts in most samples. The same suite of clay minerals occurred throughout both 9.1-m sections. The only depth function observed was the apparent presence of carbonates or soluble salts indicated by low recovery values for the particle size determinations at the greatest depths.

Mechanical analyses were made of samples from various layers between the surface and the water table. The highest clay content of 33.6% occurred in the 123- to 152-cm layer. Soils in the area with this clay content at this depth conduct water readily. All samples were either red or brown in color indicating the presence of aerobic rather than anaerobic conditions. Analyses of saturated extracts made of the samples showed that the nitrate-N level was rather constant at 4 to 6 ppm and the EC was low (108 to 732 micromhos per centimeter (µmhos/cm). From these preliminary data, it was concluded that no restricting layers existed between the soil surface and the water table.

Samples were procured down to 152 cm to determine the fertility status of the soils. These analyses indicated that the pH, potassium, calcium, soluble salts and sodium were at levels desirable for plant growth. Phosphorus additions were indicated to be necessary. The organic matter was very low, a condition common in the cultivated soils of the area.

Irrigation Well--

To insure a continuous water supply in the event of well or motor failure, two wells were drilled at the locations indicated on Figure 1. The 101.60-cm diameter holes were drilled about 18 m deep. Each well was cased with 45.72-cm diameter steel casing with a 2.4-m length of 0.32-cm slotted screen and packed with No. 4 gravel. The wells were pumped for about 48 hours at increasing flow rates.

Aquifer transmissibility is between 3105 hectoliters per day per meter (hlpd/m) and 4347 hlpd/m. The change in slope of the curve shown in Figure 2 indicates the wells receive horizontal recharge.

The wells produced increasing amounts of sand as discharge rates were increased above 1135 liters per minute (lpm). The pumps were, therefore, designed to produce a maximum of about 1135 lpm per well.

One pump was installed in the west well and two pumps were installed in the east well. The smaller pump was necessary for the automated subirrigation system.

Subirrigation Lateral Spacing--

No criteria existed for determining the proper spacing of subirrigation laterals in different soil types. Since subirrigation systems have not previously been evaluated in a Miles fine sandy loam, a preliminary study was conducted to determine if the spacing proposed was adequate to obtain good distribution of the water applied. Two polyethylene subirrigation laterals were buried 30 cm deep and water was applied. Measurements of the soil water were made with a neutron probe and by gravimetric methods. The preliminary results (Figure 3) indicated that good soil-water distribution could be obtained with the laterals on 102-cm centers.

Field Facilities

Field facilities were installed to undertake the following functions:

a. Extract soil water
b. Measure soil-water potential
c. Measure soil-water content
d. Measure climatic parameters

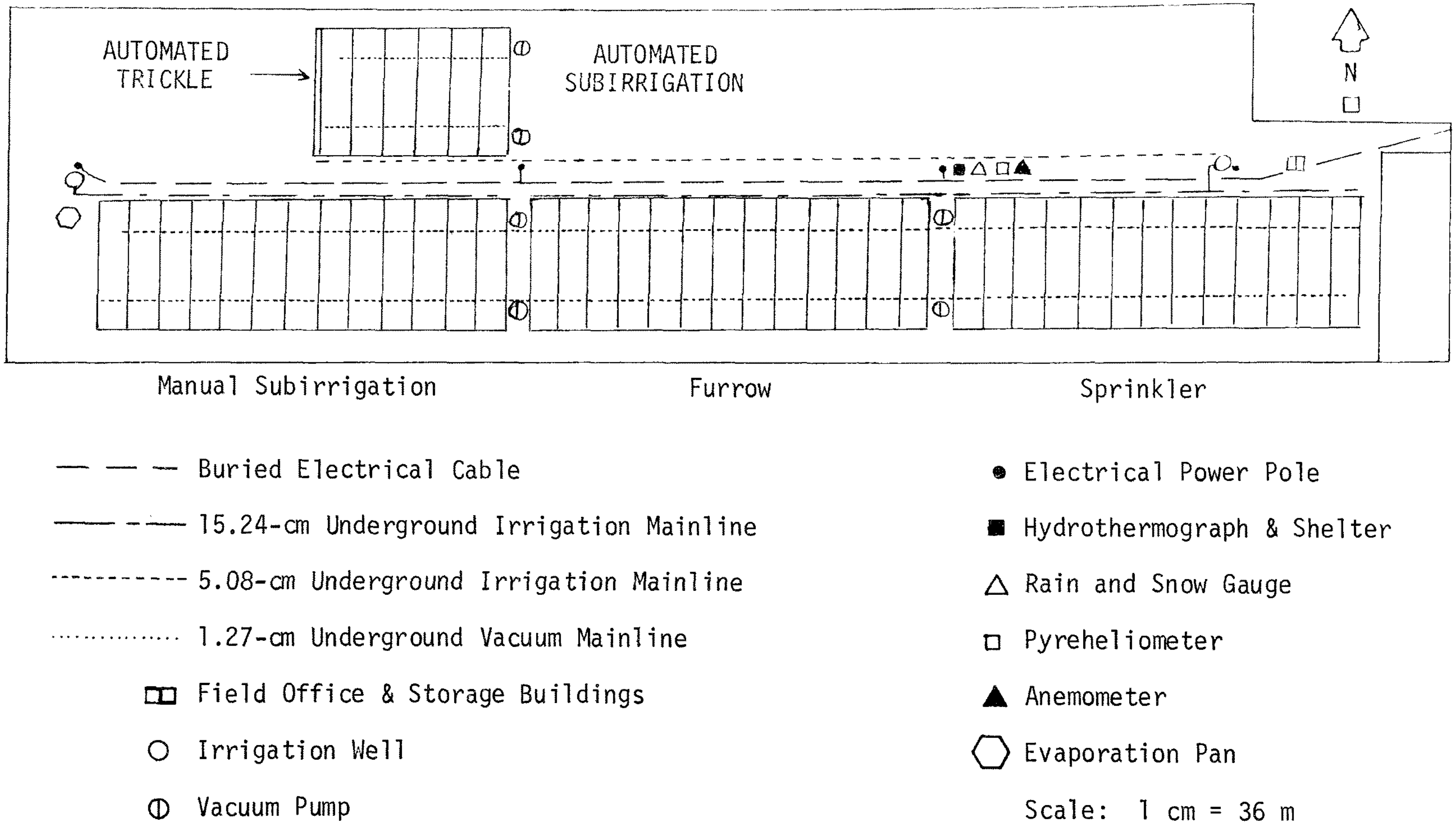


Figure 1. Location of vacuum, electrical, meteorological, and irrigation installations at the field site near Munday, Texas.

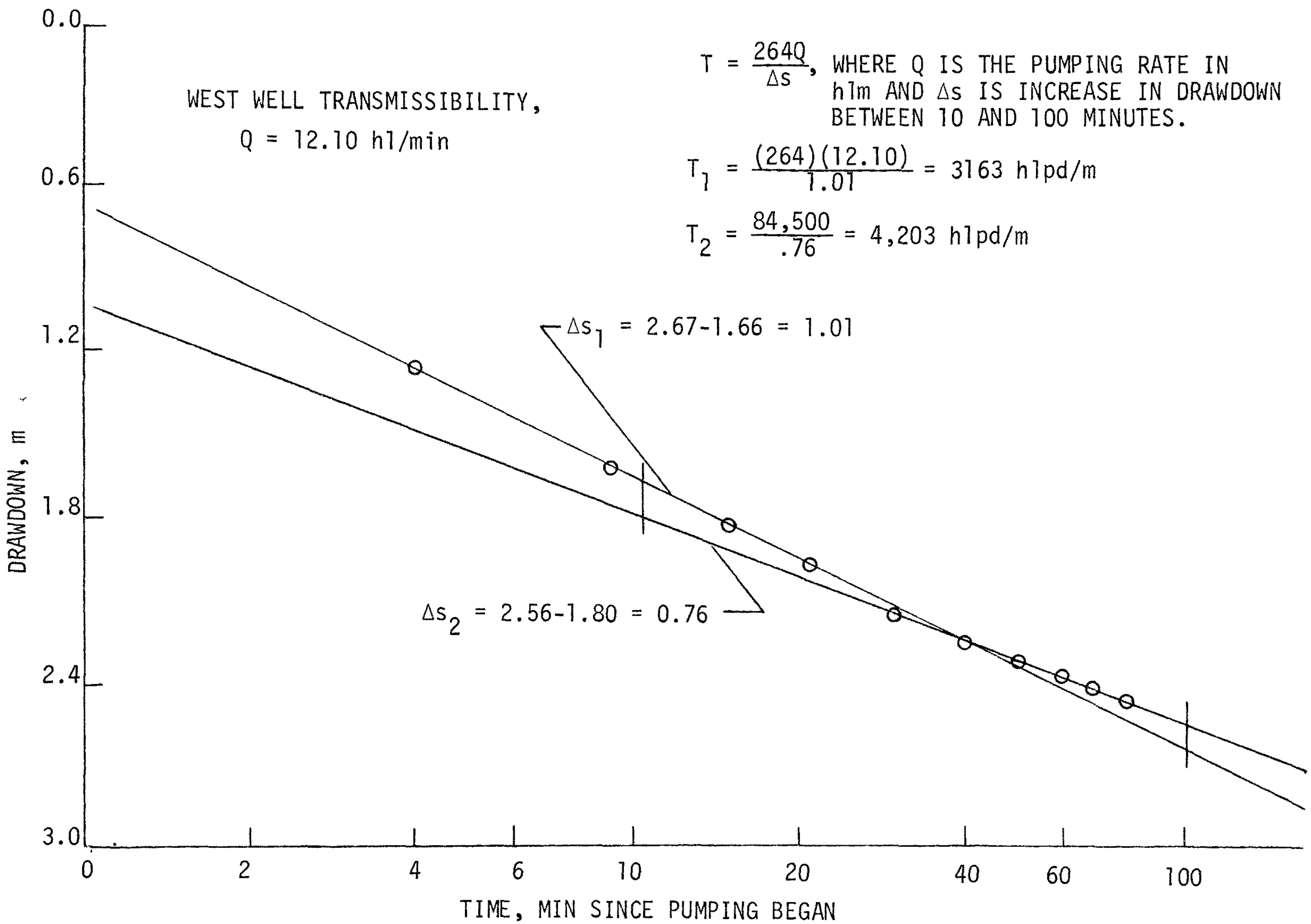


Figure 2. Transmissibility of the Seymour aquifer under the site near Munday, Texas, 1970.

e. Provide necessary electrical power to operate systems
f. Apply irrigation water

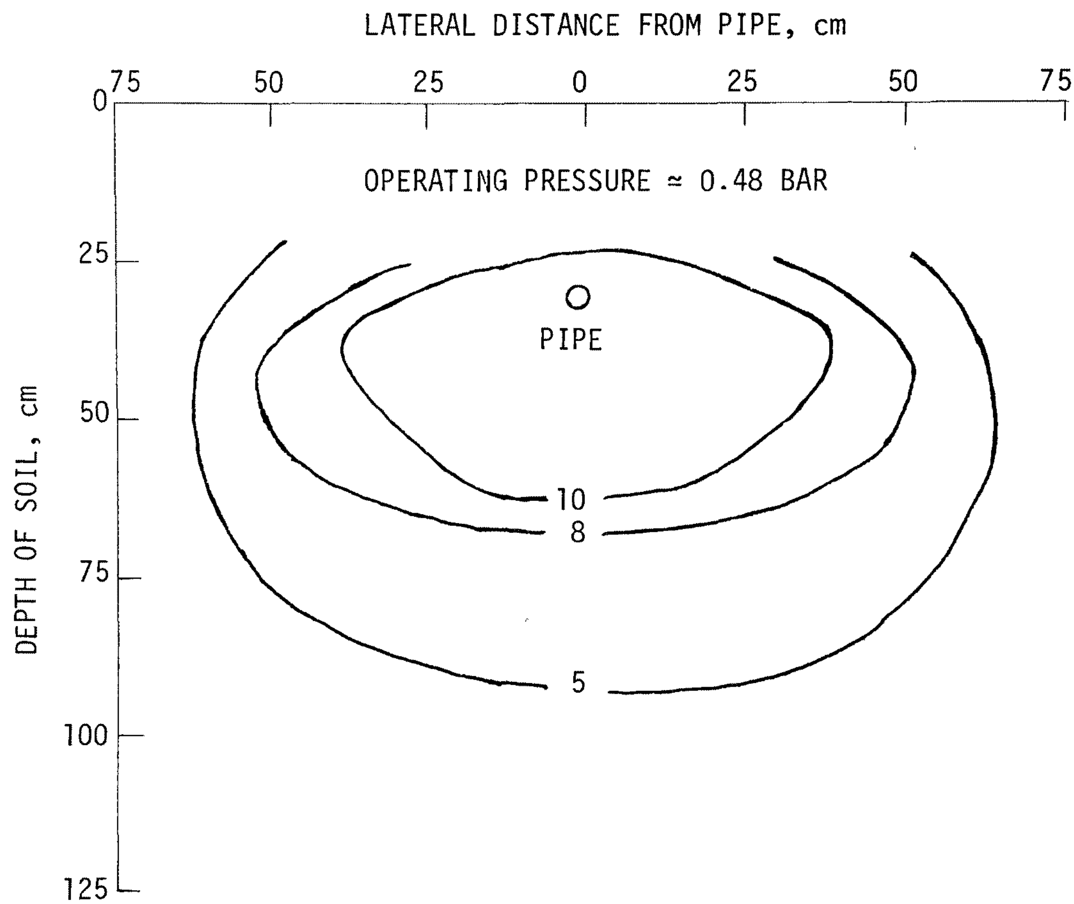


Figure 3. Moisture increase (percent by volume) and distribution 62 hours after subirrigation in a Miles loamy fine sand located on the site near Munday, Texas.

The locations of the field facilities are shown on Figure 1 and described below.

Soil-Water Extraction System--

The extraction system was composed of vacuum pumps (Models 1065 and 2065, Gast Manufacturing Company, Benton Harbor, Michigan) and soil-water extraction tubes (Soil Moisture Equipment Company, Santa Barbara, California) connected by an underground line. The underground vacuum line was originally 0.64-cm outside diameter (O.D.) nylon line which was installed at a depth of 76 cm. However, due to high friction losses, the line was replaced with 1.27-cm O.D. high density polyethylene line. Figure 4

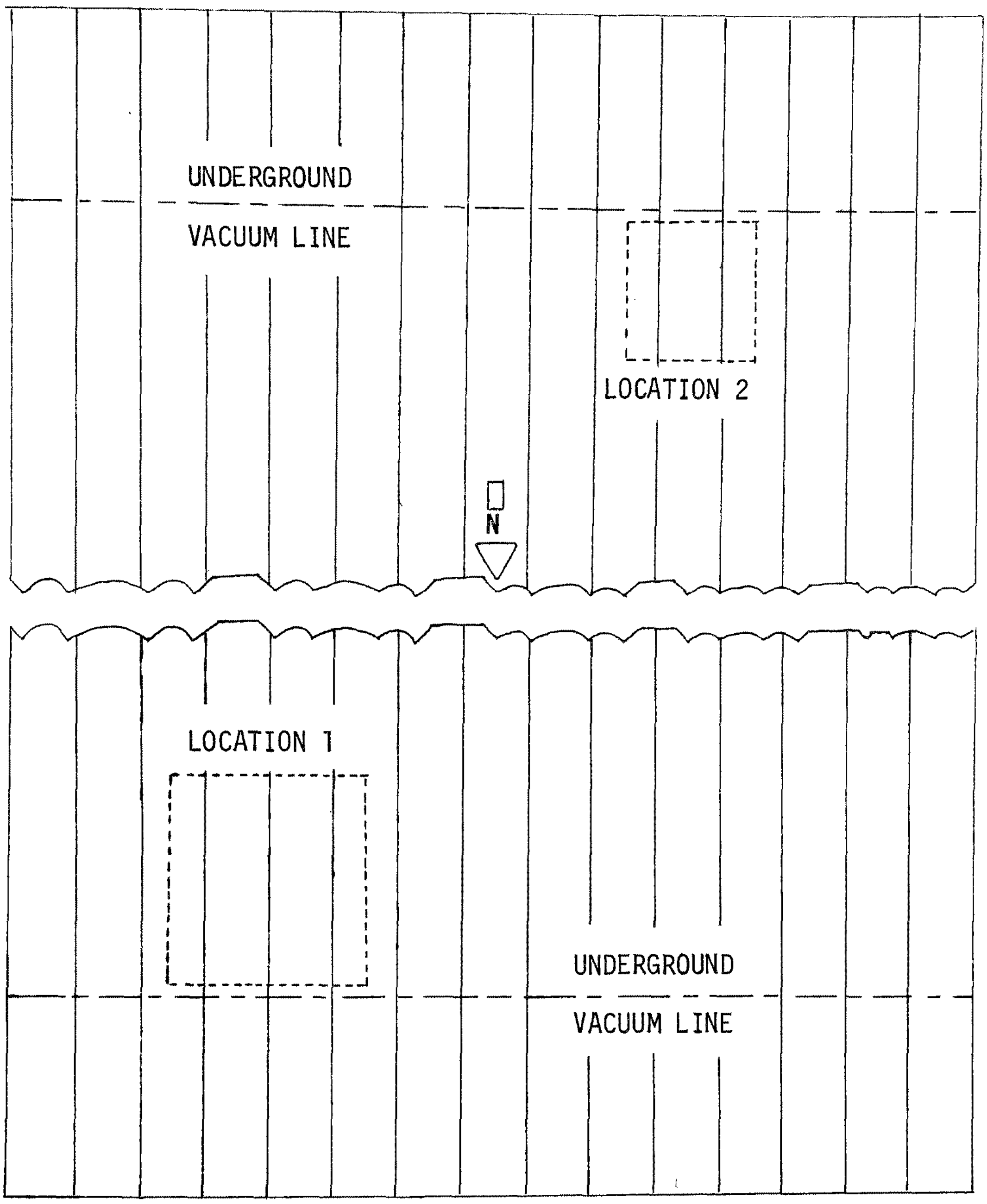


Figure 4. Location of instrumentation in each plot at field site near Munday, Texas. Plots are 16 rows wide (102-cm centers) by 67 m long. Underground vacuum line is 15.2 m from each end of plot. Soil instrumentation layouts for Locations 1 and 2 are shown in Figures 5 and 6.

shows the vacuum line in relation to the soil instrumentation in Locations 1 and 2 of each plot.

Twenty-three soil-water extraction tubes were installed in each plot. Sixteen tubes, ranging in depth from 0.15 to 9.14 m, were installed at Location 1 (Figure 5) and seven, ranging in depth from 0.15 to 1.52 m, were installed at Location 2 (Figure 6). The tubes were installed by a modified tractor-mounted press that punched a 2.22-cm diameter hole. The soil-water extraction tubes were made of 1.27-cm diameter schedule 80 polyvinyl chloride (PVC) pipe with a porous ceramic tip. A 0.32-cm O.D. nylon line was glued into the ceramic bulb and was inside the PVC pipe. The line connected the bulbs to a water sample collection bottle and a vacuum manifold. The vacuum manifolds were installed alongside the water extraction tubes. They were constructed from 1.91-cm PR-200 PVC line with holes drilled to fit a No. 00 rubber stopper. When an extraction was completed at a particular depth, the extraction tube was disconnected from the manifold. The only serious problem that occurred was the evaporation of water from the collection bottles. This was eliminated by adding mineral oil to the bottles.

Soil-Water Potential Measuring System--

Tensiometers (Model R, Irrometer Company, Riverside, California) were used to measure soil-water potential. Figures 5 and 6 show the number of tensiometers and depths of each for both locations in each plot. Tensiometers were installed by the same method used for installation of soil-water extraction tubes. The only problem encountered with this type of tensiometer was that the rubber stopper occasionally stuck to the main body and twisted off when the cap was unscrewed for servicing. The shallow depth tensiometers were serviced approximately once a week (after each irrigation) and the others approximately every two weeks.

Soil-Water Content Measuring System--

Soil-water content was measured with neutron probes inserted into permanently installed access tubes. Each plot had two neutron probe access tubes installed to a depth of 9.14 m, one at each soil instrumentation location as shown in Figures 5 and 6. These tubes were 5.08-cm diameter aluminum, installed in 5.08-cm diameter holes drilled with a modified trailer-mounted rig. Soil moisture content was monitored with two neutron moisture meters and probes (Model 2651 Scaler-Ratemeter and Model 104A Depth Moisture probes, Troxler Electronic Laboratories, Inc., Research Triangle Park, North Carolina).

It was necessary to construct standards to calibrate the neutron probes. Three soil textures were used to make standards for the purpose of calibrating neutron moisture probes. The soil textures used were: loam (42% sand, 23.3% clay), sandy loam (60% sand, 19.6% clay), and sandy loam (76% sand, 11.3% clay). The soil was obtained from different field sites and air-dried.

Containers used for the standards were 208-l oil drums. Volume was marked on the inside of the oil drums. The air-dried soil was weighed in lots equal to the desired bulk density and mixed with water in a cement

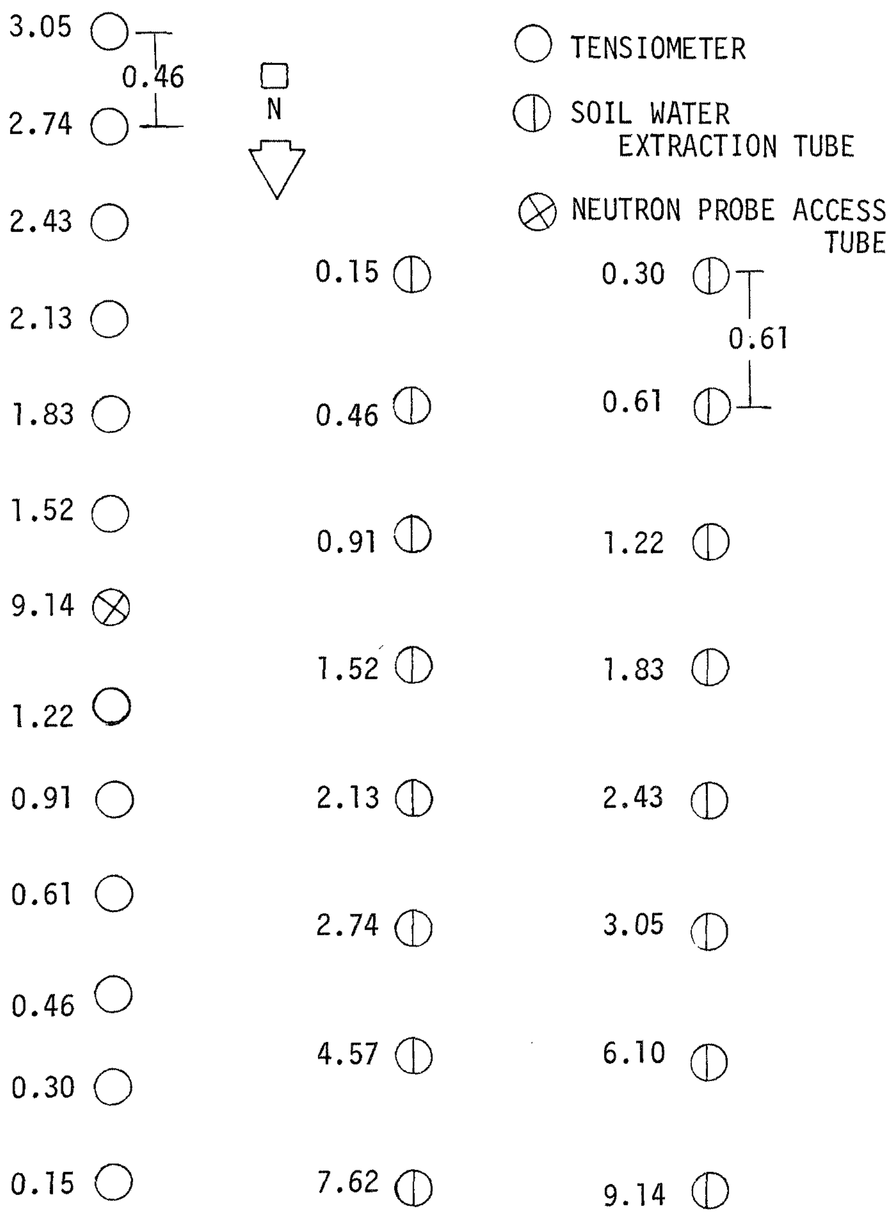


Figure 5. Soil instrumentation layout in Location 1 in each plot of the field site near Munday, Texas. Depth of each instrument is as indicated. (Depths and dimensions in meters.)

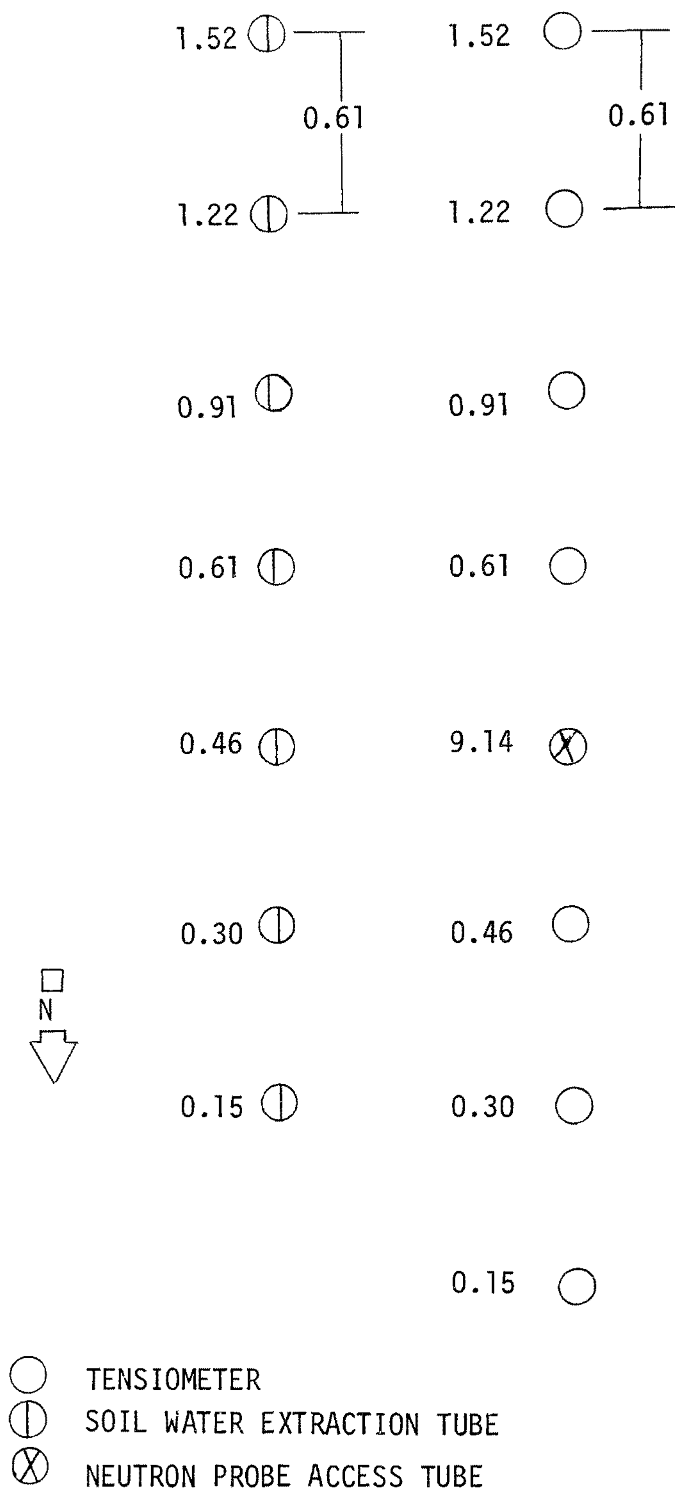


Figure 6. Soil instrumentation layout at Location 2 in each plot of the field site near Munday, Texas. Depth of each instrument is as indicated. (Depths and dimensions in meters.)

mixer to obtain the desired moisture content. After each lot was thoroughly mixed, it was dumped and covered until all lots were mixed. All lots were then mixed together to assure a homogeneous moisture content. The soil was then weighed out at its wet density in 0.28-hectoliters (hl) batches and packed in the container around the access tube. A piece of 0.64-cm plywood covered with black plastic asphalt cement was used to seal each container. Sixteen standards were made with varying moisture contents and bulk densities.

After a few neutron moisture content readings were made, it was determined that a layering effect existed due to moisture content. A soil core was taken from each container to determine the moisture content of each layer.

Bulk density was found to affect the moisture content values as determined by the neutron probe. It was necessary to determine the bulk density of each hole at the site and develop equations for each neutron probe that were based on bulk density as well as the moisture content standards. This was accomplished by use of a density probe (Model 2651, Troxler Electronic Laboratories, Inc., Research Triangle Park, North Carolina).

System for Measuring Climatic Conditions--

Figure 1 shows the layout of the meteorological instrumentation. This instrumentation consisted of the following:

(1) Hygrothermograph, Model 594, Bendix Corporation, Environmental Science Division, Baltimore, Maryland

(2) Rain and Snow Gauge, Model 775C, Bendix Corporation, Environmental Science Division, Baltimore, Maryland

(3) Microbarograph, Friez Model 790-1, Bendix Corporation, Environmental Science Division, Baltimore, Maryland

(4) Aerovane Wind Transmitter, Model 120, Bendix Corporation, Environmental Science Division, Baltimore, Maryland

Aerovane Recorder, Model 141, Bendix Corporation, Environmental Science Division, Baltimore, Maryland

Aerovane Support, Model 150, Bendix Corporation, Environmental Science Division, Baltimore, Maryland

(5) Solar Radiation Recorder, Model R-401, Weather Measure Corporation, Sacramento, California

(6) Evaporation Pan, Catalog No. 242, Science Associates, Princeton, New Jersey

(7) Totalizing Anemometer, Catalog No. 404, Science Associates, Princeton, New Jersey

(8) Volt Time Integrator, Catalog No. 618-1, Science Associates, Princeton, New Jersey

(9) Pyreheliometer, Catalog No. 636, Science Associates, Princeton, New Jersey

Electrical Power System--

The location of the buried 440 volt electrical cable is as shown in Figure 1. Another buried cable furnished 110 and 220 volts to the field office. At each well and at two power poles in the field the 440 volts were transformed to 110 volts for small electric motor use, such as those on the vacuum pumps.

Irrigation System--

The irrigation system (Figure 1) consisted of the two irrigation wells, an underground pipeline that connected the two wells, and the three types of irrigation systems - sprinkler, furrow, and manual subirrigation.

Irrigation wells and pipelines--The two irrigation wells were 17.4 m deep with a 11.2-kilowatt (kw) submersible pump set in each well. The pumping capacity of each well was approximately 927 lpm. At this rate, very little sand was pumped. A flow meter was located at each well, and the discharge passed through a sandtrap before entering the underground mainline. The underground pipeline was 15.24-cm diameter PVC. All components of the mainline pipe above the ground were steel.

Sprinkler irrigation system--The sprinkler irrigation system was solid set in a triangular pattern with sprinklers located 12.2 m apart along the laterals. The laterals were 5.08-cm diameter aluminum with 1.91-cm diameter galvanized steel risers 1.83-m tall. The sprinklers had 0.44-cm diameter brass nozzles. The flow was limited to each lateral by a 113-lpm flow control valve. With this flow, each sprinkler discharged 18.9 lpm at 2.8 bar lateral pressure.

Furrow irrigation system--The furrow plots were leveled for even distribution of water through 15.24-cm diameter gated slip-joint aluminum irrigation pipe. Gates were 5.08-cm diameter butterfly valves spaced 102 cm apart. The amount of water delivered to each plot was metered through a 15.24-cm magnetic-drive flow meter.

Manual subirrigation system--The subirrigation laterals were installed with a modified chisel at an approximate depth of 45 cm below the soil surface. There was a lateral under each row (rows on 102-cm centers). These laterals were made of 1.27-cm diameter polyethylene pipe with 0.06-cm diameter Whitney-type subirrigation orifices spaced 0.91 m apart. The laterals were connected to 5.08-cm PVC header lines on each end of the plot which were also beneath the soil surface.

Following filterings, the water entered headers on each end of the plot. The flow to each header line was controlled by a 56.7-lpm flow control valve. Thus, the total flow to each plot was limited to 113 lpm. Filter cartridges (350 micron) were used in the filtering system.

Automated subirrigation system--A 5.08-cm PVC mainline was installed from the pressure tank at the east well to furnish water for these plots. The pump that furnished water for the pressure tank pumped approximately 95 lpm. The pressure switch on the tank was set at a 2.8 to 4.1 bar pressure range. A 113-lpm filter was installed in the mainline to filter the water. Filter cartridges (100 micron) were used.

Six plots (Figure 1) were installed for the automated subirrigation system with dimensions of 16 102-cm rows wide and 67 m long. Polyethylene laterals, 1.27-cm diameter, with insert orifices spaced every 0.91 m were installed on 102-cm centers at a 25- to 30-cm depth with a chisel plow. PVC header lines, 5.08-cm diameter, were installed at each end of the plots to insure uniform water distribution. The laterals were connected to the header line with 1.59-cm O.D. Tygon tubing by drilling a 1.43-cm hole in the header pipe and inserting the Tygon tubing into the hole. The other end of the Tygon tubing was slipped into the lateral and clamped.

The control valves for each plot consisted of a 120 VAC normally closed solenoid valve (Valve No. 21106021, Hays Manufacturing Company, Erie, Pennsylvania), a 37.8-lpm flow control valve for each header pipe, and necessary gate valves for flushing.

An automated trickle-irrigated plot was also installed with the automated subirrigation plots. It was six 102-cm rows wide and 67 m long. The laterals were the same as used for the subirrigation system. They were connected to a 1.91-cm PVC header line with slip-joint connectors and plugged on the other end. The amount of water delivered to the plot was controlled by a 56.8-lpm flow control valve. Controls for the plots are described in a publication by Wendt, et al. (23).

Models

Hydraulic Conductivity--

One of the major parameters affecting water and ion movement is the hydraulic conductivity of the soil profile. The method used to determine hydraulic conductivity was that of Hillel, et al. (9) which is described by the following equation

$$K = (dW/dt)Z/(\partial H/\partial Z)Z \qquad [1]$$

where K = hydraulic conductivity
$(dW/dt)Z$ = change in water content with time at depth Z
$(\partial H/\partial Z)Z$ = hydraulic gradient at depth Z.

As will be discussed later, the soil texture varied considerably below the soil surface. It was necessary to select sites with the range of soil textures to obtain the necessary range of hydraulic conductivities. Three sites with a range of soil textures between 0 and 3 m were located for the hydraulic conductivity study. Plots 6 x 6 m were used in the study. Tensiometers and neutron probe access tubes were installed in triplicate near the center of each plot (Figure 7). Tensiometers were installed at random to a depth of 3 m and access tubes were installed to 3.7 m. Soil samples

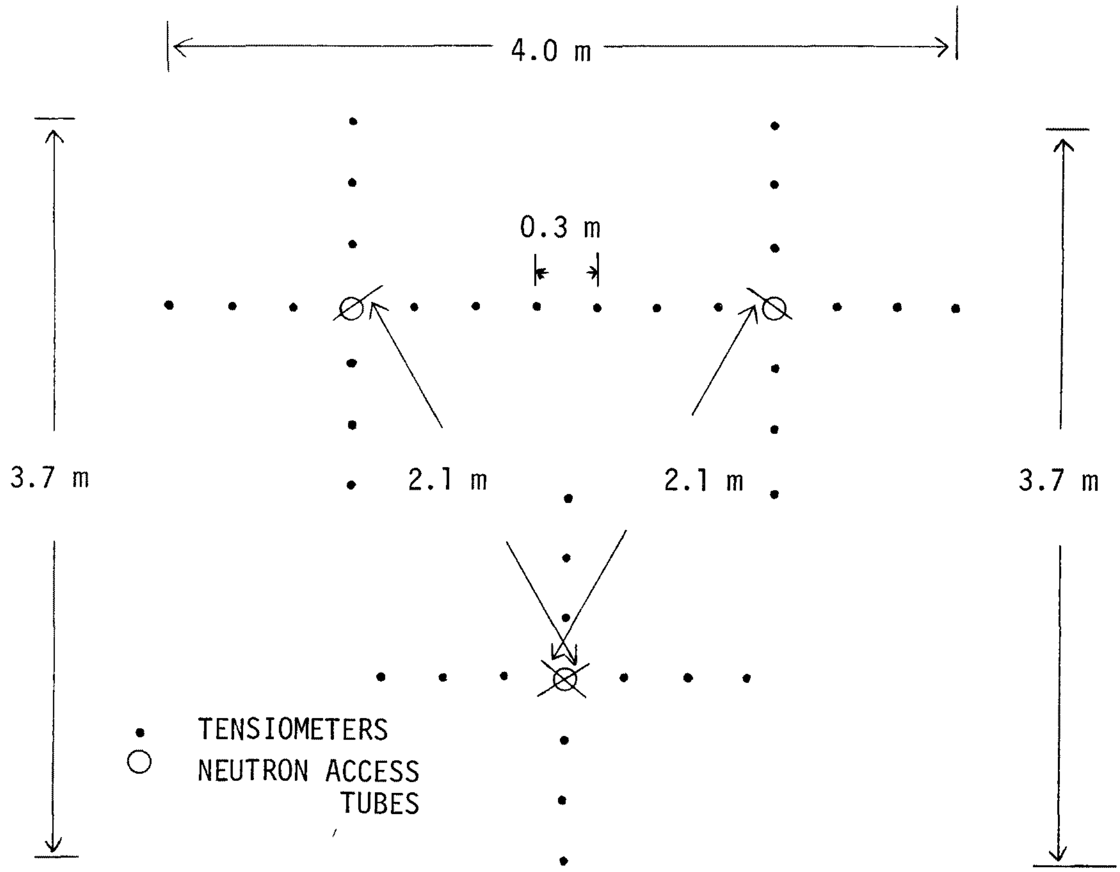


Figure 7. Plot design used in hydraulic conductivity studies in Knox County, Texas. (Tensiometers spaced at 0.3-m intervals at random depths to 3.0 m around each access tube. Neutron access tubes spaced 2.1 m apart in an equilateral triangle to 3.7-m depth.)

for textural analysis were obtained at 0.30-m intervals at the time the neutron probe access tubes were installed. Bulk densities at 0.30-m intervals were determined for each hole using a calibrated bulk density probe.

Water Balance--

The total water balance of the root zone has been presented by Hillel (8) as follows

$$\Delta W = M + Ir - N - F - (E + T) \qquad [2]$$

where
- ΔW = change in root-zone water content
- M = precipitation
- Ir = irrigation water applied
- N = runoff
- F = deep percolation
- $E + T$ = evaporation + transpiration or evapotranspiration (ET).

Precipitation and irrigation water applied can be easily measured. Runoff can be prevented or measured. Deep percolation and ET losses can be determined by quantitative measurements of soil-water content.

One method of assuring that a minimum amount of water is available for deep percolation is to apply only that necessary for ET. One commonly used approach is to evaluate some method for estimating ET. The model evaluated in this study is that of Penmann, further developed by Jensen, et al. (10). The Jensen model, commonly used in the western United States, is

$$E^* = \frac{\Delta}{\Delta + \gamma} \left(R_n\right) - G + \frac{\gamma}{\Delta + \gamma} (15.36)\ (1.0 + 0.01W)\ e_s - e_d \qquad [3]$$

where E^* = evaporative flux (latent heat)
Δ = slope of the saturation vapor pressure-temperature curve (de/dT)
γ = psychrometric constant
e_s = mean saturation vapor pressure (mean at maximum and minimum daily air temperature)
e_d = saturation vapor pressure at mean dew point temperature
W = total daily wind run
R_n = daily net radiation
G = daily soil heat flux.

Where day-to-day temperatures do not change greatly and day-to-day radiation is similar, soil heat flux (G) is relatively small during the summer months and can be neglected.

Net radiation values are necessary for the above model. Such measurements are difficult to obtain and not readily available. However, procedures have been developed for estimating net radiation using observed solar radiation for a day. Cloudless day values can be obtained from estimates by Fritz (5) or by plotting clear day values to obtain an envelop curve through the high points as follows

$$R_n = (1 - \alpha)R_s - R_b \qquad [4]$$

where α = albedo
R_s = observed daily solar radiation
R_b = net outgoing long wave radiation

R_b can be estimated as follows

$$R_b = (aR_s/R_{so} + b)R_{bo} \qquad [5]$$

where R_{so} = solar radiation on a cloudless day
R_{bo} = net outgoing long wave radiation on a clear day which was estimated as follows

$$R_{bo} = [0.98 - (0.66 + 0.044\sqrt{e_d})]\ (11.71 \times 10^{-8})\ \frac{T2_A^4 + T1_A^4}{2} \qquad [6]$$

where e_d = saturation vapor pressure at mean dew point temperature

11.71×10^{-8} = Stefan-Boltzmann constant

$T2_A$ and $T1_A$ = maximum and minimum daily air temperatures.

A plant factor is necessary to fully utilize the ET potential model of Jensen (10) since the ET of a system with small plants is less than a system with large plants and is not equal to the potential ET. Ritchie (21) has shown that the ET of a crop is related to the leaf area of the crop. Equations were developed to determine leaf area using stem diameter to evaluate the Jensen model. The generalized equations used were

$$\text{Log } Y = a + b \text{ Log } X \qquad [7]$$
$$\sqrt{y} = a + b\sqrt{x}$$

where y = leaf area

x = stem diameter 2.54 cm above the ground.

Stem diameter measurements were made every two weeks on 10 plants in 11 plots.

Treatments

Portions of the field site were not suited for furrow irrigation because of the undulating topography. The most level land was near the center of the site. Therefore, plots were grouped by method of irrigation and, to facilitate irrigation, by moisture level. Irrigation, fertilizer treatments and treatment arrangements for the four years are listed in Table 1.

To simplify field operations, plots were numbered from east to west (Figure 1). Plots 1 through 13 were sprinkler-irrigated, Plots 14 through 26 were furrow-irrigated, and Plots 27 through 39 were subirrigated. For ease of reference, plot numbers and fertilizer treatments are listed in Table 1. The north half of each plot was designated as Location 1, and the south half as Location 2.

Plots in the M1 moisture treatment were irrigated when the upper leaves of the corn began to curl at midday. Plots in the M2 moisture treatment were irrigated when the soil-water potential at the 15-cm depth declined to -20 or -30 cb. Plots in the M3 moisture treatment were irrigated when the soil-water potential at the 15-cm depth declined to -40 or -60 cb. The -30 and -60 cb potentials were used during the first year (1971) for the respective levels. However, severe stress developed during critical stages of growth on the -60 cb plots, and the levels were changed to -20 and -40 cb levels, respectively, for the remaining years. The automated subirrigation plots had switching tensiometers set at 30 cm which activated the systems

TABLE 1. FERTILIZER AND IRRIGATION TREATMENTS FOR THE 1971-1974 CROP YEARS AT THE KNOX COUNTY, TEXAS, FIELD SITE

Plot no.	YEAR 1971	1972	1973	1974
1	M3 F11	M3 F11	M3 F11	
2	M3 F6 A3	M3 F6 A3	M3 F6 A2	
3	M3 F6 A2	M3 F6 A2	M3 F6 A2	
4	M3 F4 A2	M3 F4 A2	M3 F4 A2	
5	M3 F2 A2	M2 F1 A2	M3 F1 A2	
6	M2 F11	M2 F11	M2 F9	M2 F10 A2
7	M2 F6 A3	M2 F6 A3	M2 F7 A3	M2 F6 A3
8	M2 F6 A2	M2 F6 A2	M2 F7 A2	M2 F6 A2
9	M2 F4 A2	M2 F4 A2	M2 F5 A2	M2 F4 A2
10	M2 F2 A2	M2 F8 A2	M2 F1 A2	
11	M1 F11	M1 F11	M2 F11	M2 F11
12	M1 F6 A2	M1 F6 A2	M1 F6 A2	M2 F7 A2
13	M1 F1 A2	M1 F1 A2	M1 F1 A2	M2 F3 A2
14	M3 F11	M3 F11	M3 F11	
15	M3 F6 A3	M3 F6 A3	M3 F6 A3	
16	M3 F4 A2	M3 F4 A2	M3 F4 A2	
17	M3 F2 A2	M2 F1 A2	M3 F1 A2	
18	M2 F11	M2 F11	M2 F9 A2	M2 F10 A2
19	M2 F6 A3	M2 F6 A3	M2 F7 A3	M2 F6 A3
20	M2 F4 A2	M2 F4 A2	M2 F5 A2	M2 F4 A2
21	M2 F2 A2	M2 F8 A2	M2 F1 A2	
22	M1 F11	M1 F11	M2 F11	M2 F11
23	M1 F6 A2	M1 F6 A2	M1 F7 A2	M2 F6 A2
24	M1 F6 A1	M1 F6 A1	M1 F7 A1	M2 F6 A1
25	M1 F1 A2	M1 F1 A2	M1 F1 A2	M2 F3 A2
26	M1 F1 A1	M1 F1 A1	M1 F1 A1	M2 F3 A2
27	M3 F11	M3 F11	M3 F11	
28	M3 F6 A3	M3 F6 A3	M3 F6 A3	
29	M3 F6 A2	M3 F6 A2	M3 F6 A2	
30	M3 F4 A2	M3 F4 A2	M3 F4 A2	
31	M3 F2 A2	M2 F1 A2	M3 F1 A2	
32	M2 F11	M2 F11	M2 F9	M2 F10 A2
33	M2 F6 A3	M2 F6 A3	M2 F7 A3	M2 F6 A3
34	M2 F6 A2	M2 F6 A2	M2 F7 A2	M2 F6 A2
35	M2 F4 A2	M2 F4 A2	M2 F5 A2	M2 F3 A2
36	M2 F2 A2	M2 F8 A2	M2 F1 A2	
37	M1 F11	M1 F11	M2 F11	M2 F11
38	M1 F6 A2	M1 F6 A2	M1 F6 A2	M2 F7 A2
39	M1 F1 A1	M1 F1 A2	M1 F1 A2	M2 F3 A2
40		M4 F6 A2	M4 F7 A2	M4 F6 A2
41		M4 F6 A2	M4 F7 A3	M4 F6 A3
42		M4 F11	M4 F11	M4 F11
43		M5 F6 A2	M5 F6 A2	M5 F6 A2
44		M5 F6 A3	M5 F6 A3	M5 F6 A3
45		M5 F11	M5 F11	M5 F11
46		M4 F6 A3	M4 F7 A3	M4 F6 A3

Legend for irrigation and fertility treatments

Irrigation system:

Plots 1 - 13 - Sprinkler
14 - 26 - Furrow
27 - 39 Manual Subirrigation
40 - 45 - Automated Subirrigation
46 - Automated Trickle Irrigation

Moisture level:

M1 - High Moisture level based on growth (significant upper leaf curl at midday)
M2 - High Moisture level based on potential at 15.24 cm, -30 cb in 1971, -20 cb in 1972, 1973, 1974
M3 - Moderate Moisture level based on potential at 15.24 cm, -60 cb in 1971, -40 cb in 1972, 1973, 1974
M4 - Constant High Moisture level based on potential at 30.48 cm, -20 cb
M5 Constant Moderate Moisture level based on potential -40 cb

Fertilizer sources:

F1 - Anhydrous Ammonia
F2 - Anhydrous Ammonia + N-Serve
F3 - Anhydrous Ammonia + Sodium Bromide
F4 - Sulfur Coated Urea
F5 - Sulfur Coated Urea + Sodium Bromide
F6 - Nitrogen Solution
F7 - Nitrogen Solution + Sodium Bromide
F8 - Sodium Nitrate + Sodium Bromide
F9 - Sodium Nitrate + two small plots of ^{15}N-enriched Sodium Nitrate + Sodium Bromide
F10- Sodium Nitrate + 1/2 of two small plots in F9 fertilized with ^{15}N-enriched Sodium Nitrate
F11- Control

Method of fertilizer application:

A1 - Chiseled Below Bottom of Water Furrow
A2 - Chiseled Above Bottom of Water Furrow
A3 - Applied in Irrigation Water

when soil-water potentials reached -20 and -40 cb for the M4 and M5 treatments. In general, the potentials dropped to -10 and -30 cb in the M4 and M5 levels following moisture additions due to a lag in the movement of the applied water to the tensiometers. However, since water was not lost from the root zone, the lag was not considered significant.

Initially, fertilizer materials used in 1971 were chosen because of the following potential advantages. Anhydrous ammonia containing 82% nitrogen is commonly used and costs less. "N-Serve" contains a bacteria inhibitor which slows the rate of nitrification and thus should reduce the amount of leachable nitrate present in the soil at any particular time. The sulfur coating around urea is gradually desolved and decomposed by soil organisms and thus should gradually release nitrogen as it is needed by plants. Nitrogen solutions are easily applied with irrigation water and thus facilitate "spoon-feeding" of the crop.

Plots to which the N-Serve was added to anhydrous ammonia did not show a yield advantage during the 1971 growing season, and the plots that received this treatment were either fertilized with anhydrous ammonia (Plots 15, 17, 30) or sodium nitrate (Plots 10, 21, 36) in 1972 (Table 1). Sodium nitrate was used as a nitrate-N source. Sodium bromide was applied with the sodium nitrate to determine the usefulness of bromide as a tracer for fertilizer nitrate in soils.

In 1973, Plots 5, 17 and 31 were returned to the M3 or moderate moisture level since Plots 10, 21 and 36 were fertilized with anhydrous ammonia. Plots 6, 18 and 32, previous control plots for the M2 moisture level, were used for the ^{15}N tracer study. The ^{15}N-enriched fertilizer as sodium nitrate and sodium bromide was applied to two 6 x 6 m subplots within each of the main plots. The enriched fertilizer and sodium bromide were applied in a water solution through a chisel for more precise application. The subplots were located adjacent to the existing instrumentation locations and sampled with a high clearance soil coring rig specifically designed for the study (1). Plots 11, 22 and 37 were used as control plots for both the M1 and M2 moisture levels since both were high moisture level treatments.

In addition to these changes, sodium bromide was applied to Plots 7, 8, 9, 19, 20, 23, 24, 33, 34, 40 and 41 and a trickle plot to determine the movement of fertilizer nitrates by the various irrigation methods. The bromide was applied to six rows (two rows on either side of the two rows containing the soil-water sampling tubes).

Not all plots were utilized in 1974 since the only additional information needed to complete the objectives of the project were on the fate of ^{15}N and movement of fertilizers below the root zone. Plots 1-5, 10, 14-17, 21 and 27-31 were not included in the study in 1974. Sodium bromide was applied as a tracer to those plots that received excess water (Plots 12, 13, 25, 26, 38, 39).

In 1974, ^{15}N-enriched sodium nitrate was applied to one-half (3 x 6 m) of the original 6 x 6 m plot fertilized with ^{15}N in 1973. The other half of the plot was fertilized with an equal rate of unenriched sodium nitrate.

Enrichment levels of ^{15}N were 6.2 atom percent in 1973, 7.0 atom percent at the planting application in 1974, and 6.4 atom percent for the sidedress application in 1974.

Laboratory Facilities and Procedures

A laboratory was established at the Texas A&M University Vegetable Research Station at Munday to make the necessary analyses on soil, water and plant samples from the field site. Chemical analyses were determined by an AutoAnalyzer (Model CSM-6, Technicon Industrial Systems, Tarrytown, New York) which operates as follows: A sample stream from an automatic sampling device is divided into seven individual streams for analysis. Each stream passes through one of two proportioning pumps which meter sample, reagent, and air bubbles to segment the streams. The sample stream may also be automatically diluted with distilled water if high concentrations are expected. Six of the streams pass through mixing coils for reaction and color development. After reaction, streams are fed to sample flowcells in the colorimeter where they are debubbled and colorimetrically analyzed using a common light source and appropriate filters. Phototubes furnish input signals for a signal conditioner, where the signals are amplified and recorded on a continuous recording strip chart recorder. The seventh stream is aspirated into a dual channel flame photometer.

The AutoAnalyzer was programmed to make the analyses by the following methods:

Nitrate and Nitrite--

Nitrate was reduced to nitrite by a copper-cadmium reductor column. The nitrite ion reacted with sulfanilamide under acidic conditions to form a diazo compound. This compound coupled with N-Napthylethylenediamine to form a reddish-purple Azo dye. The final product measured represented the nitrite ion originally present plus that formed from the nitrate. Original nitrite was simultaneously determined on a separate channel without the reductor column. Nitrate concentration was then determined by subtraction.

Chloride--

The automated procedure for the determination of chloride depends on the liberation of thiocyanate ion from mercuric thiocyanate by the formation of un-ionized but soluble mercuric chloride. In the presence of ferric ion, the liberated thiocyanate forms highly colored ferric thiocyanate, in concentration proportional to the original chloride concentration.

Ammonium--

The procedure for determining ammonium utilizes the Berthelot Reaction in which the formation of a blue-colored compound believed to be closely related to indophenol occurs when the solution of an ammonium salt is added to sodium phenoxide followed by the addition of sodium hypochlorite. A solution of potassium sodium tartrate (Rochelle Salts) is added to the sample stream to eliminate the precipitation of the hydroxides of heavy metals which may be present.

Orthophosphate--

Orthophosphate was determined by the well-known method whereby ammonium molybdate reacts in an acid medium to form molybdophosphoric acid which is then reduced to the molybdenum blue complex by reaction with ascorbic acid.

Sulfate--

Sulfate was determined by a turbidimetric analysis procedure. The sample or distilled water wash was continuously aspirated into the analytical system. A three-way solenoid valve was used to add sequentially barium chloride and a sodium salt of ethylenediamine tetraacetic acid (EDTA) to the sample at precise time intervals. The sequential introduction of the sodium salt of EDTA during the wash cycle prevented the accumulation of barium sulfate on the flow cell walls, thus preventing base line drift on the recorder. Barium chloride reagent reacted with sulfate in the sample to form an insoluble barium sulfate suspension. The barium chloride reagent was acidified to prevent precipitation of carbonate, chromate, phosphate, and oxalate of barium. Gelatin was used to hold the barium sulfate in suspension.

Calcium, Potassium and Sodium--

Calcium, potassium and sodium were determined by flame emission using a dual channel flame photometer with lithium as an internal standard. As the flame photometer was limited to only two channels in 1971, it was necessary to pass all samples through the AutoAnalyzer again for determination of the third cation.

In order to minimize manual dilutions of samples, the AutoAnalyzer was calibrated to operate in the following ranges:

Nitrate + Nitrite	0 - 100 ppm
Nitrite	0 - 5 ppm
Chloride	0 - 300 ppm
Ammonium	0 - 10 ppm
Orthophosphate	0 - 10 ppm
Sulfate	0 - 500 ppm
Calcium	0 - 300 ppm
Sodium	0 - 300 ppm
Potassium	0 - 100 ppm

Standard curves were recorded preceding and following each series of 95 samples. Concentrations of unknowns were determined from chart readings by deriving the equations of the standard curves with a programmable computer and substituting values.

Total salt concentration of each sample was determined through EC made with a conductivity bridge (Model RC 16B2, Beckman Scientific Process Instruments Division, Fullerton, California).

Few 1971 soil-water extract samples had contained more than 0.1-ppm nitrite or 5-ppm phosphate and both analyses were discontinued in succeeding seasons. Colorimetric analyses for calcium and magnesium were substituted for nitrite and phosphate on the AutoAnalyzer so that analyses for all eight ions could be completed in one run. Calcium was determined via its reaction with glyoxyl-2-hydroxayanil reagent. Iron is complexed with triethanolamine (TEA), a buffer is added to control pH, and a red color results when potassium cyanide (KCN) and 2,2-(ethanediylidenedinitrilo-diphenol) are added. The determination of magnesium is based on the development of a blue complex between magnesium hydroxide ($MgOH_2$) and magnesium blue. Magnesium hydroxide is precipitated in an alkaline solution, and magnesium blue dye is absorbed in the presence of a wetting agent in a suspending material, polyvinyl alcohol (PVA). A compensating reagent is added to mask possible interferences. Iron is complexed with TEA. Calcium is complexed with ethyleneglycol bis(aminoethylether) tetraacetic acid (EGTA), and silica is complexed with sodium fluoride (NaF).

Bromide was used as an indicator in the study of sampling technique efficiency. Analyses of bromide in soil-water extracts and extracts from soil samples were made with a bromide electrode (Model 94-35, Orion Research Inc., Cambridge, Massachusetts). The electrode sensing element is a silver halide/silver sulfide membrane, which is an ionic conductor for silver. The potential developed within the electrode is fixed, so that the electrode develops potentials due only to changes in the sample silver ion activity. Even though the original sample may not contain silver ions, a very few are produced by the extremely small solubility of the silver halide membrane. The silver ion activity depends on the halide ion activity in the sample solution. Although there was interference between bromide and chloride, it was possible to compensate for the interferences by solving equations which describe the interferences (18).

Some changes were also made in laboratory procedures in 1973 to process samples for $^{15}N/^{14}N$ isotope-ratio analyses. Soil samples were air-dried, ground with a hammer mill, and extracted with equal amounts (weight/volume) of 2N sodium sulfate. The soil solutions were centrifuged to remove suspended soil and analyzed for nitrate and ammonium with the AutoAnalyzer.

A Kjeldahl digestion-distillation unit (Catalog No. S-63215, Sargent-Welch Scientific Company, Dallas, Texas) was used in the ^{15}N study. Extracts of samples selected for isotope-ratio analysis were treated with magnesium oxide and ammonium was distilled. De'Varda's alloy was then added to convert nitrate to ammonium and ammonium (of nitrate source) was distilled into a separate receiver. The ammonium fractions were concentrated and transferred to small vials for isotope-ratio analyses at another laboratory.

Total nitrogen analyses were performed on most soil samples from ^{15}N-treated plots. Soil samples were treated with potassium permanganate, reduced iron, and sulfuric acid to convert nitrate to ammonium. The organic fraction was subsequently converted to ammonium by boiling the sample in sulfuric acid and a mixture of copper sulfate, potassium sulfate, and selenium. After digestion was complete, sodium hydroxide was added, and ammonium was distilled and concentrated for isotope-ratio analysis.

Procedures used for the ^{15}N analyses were those presented by Bremner (3). A mass spectrometer (Model 21-104, Consolidated Electrodynamics Corp., Pasadena, California), located at the Trace Analysis Institute, Texas A&M University, College Station, Texas, was used for the isotope-ratio analyses in 1973 while a mass spectrometer (Model 21-620, Consolidated Electrodynamics Corp., Pasadena, California), located at the Chemistry Department, Texas Tech University, Lubbock, Texas, was used to analyze the samples obtained in 1974.

LUBBOCK LOCATION

A prototype of the proposed automated subirrigation system for the Munday site was installed at the Texas A&M University Agricultural Research and Extension Center at Lubbock during May and June of 1971. The system was evaluated and modifications were made during the growing season of 1971. The field layout consisted of two plots (Figure 8). Each plot was 16 102-cm rows wide and 67 m long. The 67-m laterals were centered on 102-cm bedded rows and chiseled to a depth of 30 cm. The laterals were 1.27-cm diameter polyethylene plastic pipe with nylon insert orifices (Figure 9) every 0.91 m along the laterals. The main and header pipes consisted of 5.08-cm PVC pipe. The 5.08-cm main pipe was designed to deliver well water to each of the header pipes within each plot. A header pipe was installed on opposite ends of 67-m laterals to reduce the pressure drop within the laterals. Two 1.27-cm, 9.46-lpm flow control valves and one 1.91-cm 120V/10amp normally closed solenoid controlled both the flow and flow rate into each set. Controls for opening the solenoid have been described in a publication by Wendt, et al. (23).

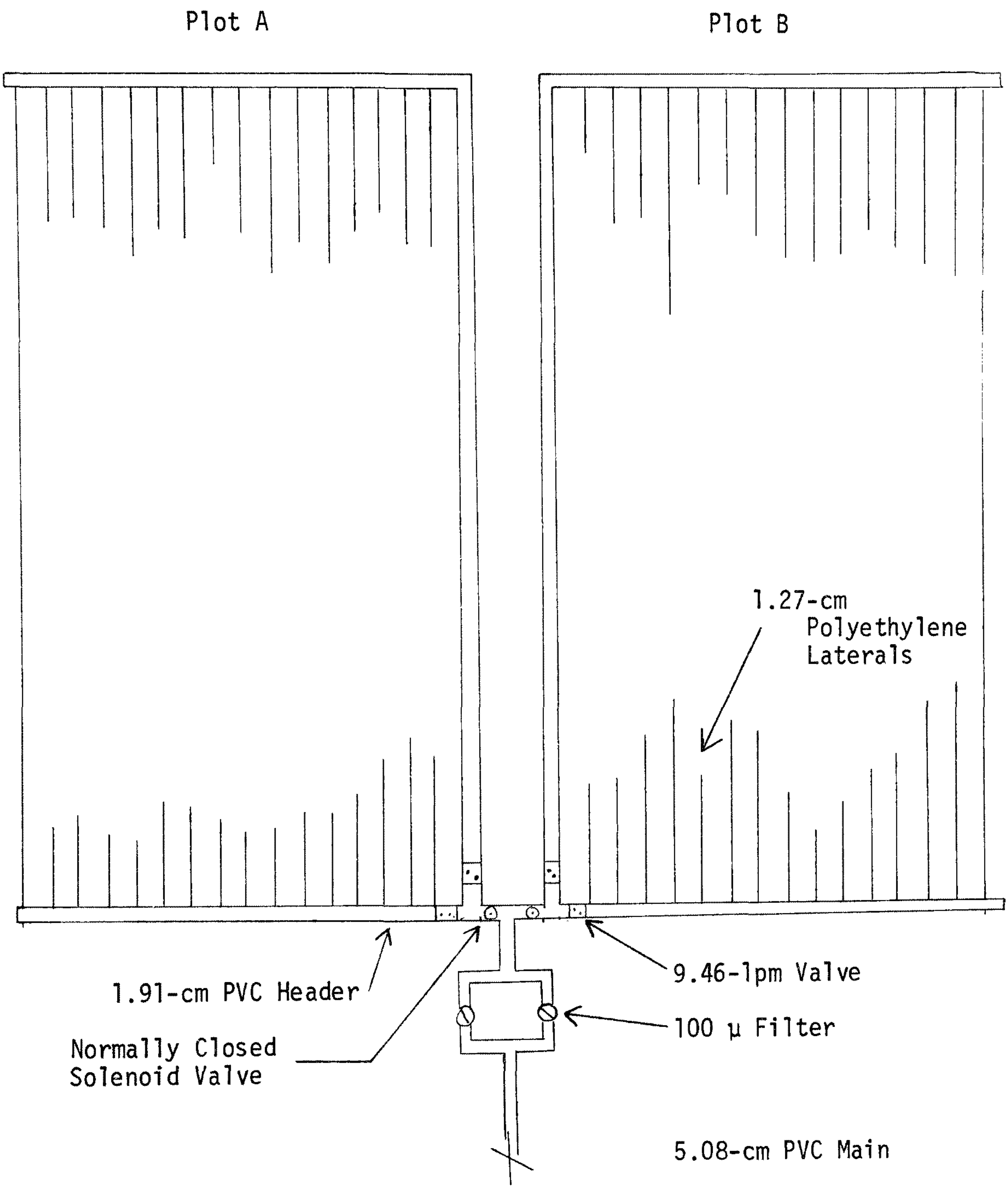


Figure 8. Subirrigation system layout at the field site at Lubbock, Texas. Each plot is 16 rows wide (102-cm centers) by 67 m long.

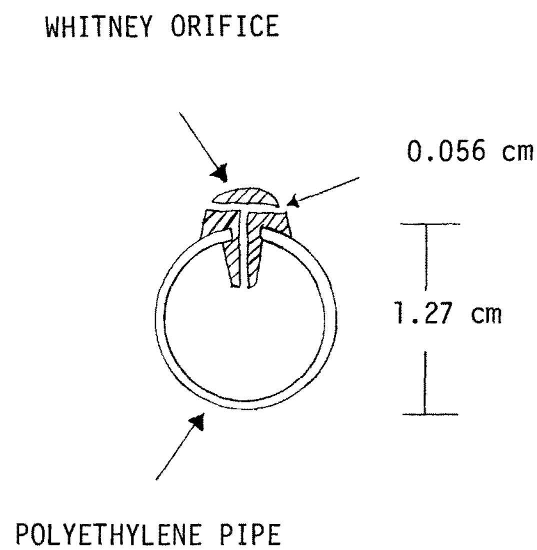


Figure 9. Schematic of orifice inserted in plastic pipe in subirrigation systems at Munday, and Lubbock, Texas.

SECTION 5

EXPERIMENTAL PHASE

MUNDAY LOCATION

Many endeavors related to this project were necessary to all objectives. It is the purpose of this section to summarize this information so that the objectives can be discussed without duplication of information. Further, a voluminous amount of data were obtained during the four years of the project. Only data most pertinent to the objectives will be included in this report. Appendices of all data are available and may be obtained by contacting either the authors or the U. S. Environmental Protection Agency. Activities which were necessary for all objectives were the recording of cultural information and measurement of climatic, plant and soil parameters. A discussion of each of these activities follows.

Cultural Information

Pertinent Information on Planting, Pesticide Applications and Harvesting--

Pertinent information on planting, pesticide applications, and harvesting is presented in Table 2. Some problems occurred in planting during the first two years of the study. During the first year, the initial planting in the furrow resulted in a low plant population, and the crop was replanted on the bed. There was some problem in obtaining emergence on the subirrigated plots when they were planted on the bed. It was necessary to apply up to 20 cm of water to obtain emergence. Plots 27, 28, 32, and 33 were replanted on July 2 in the furrow to see if it would be possible to obtain good emergence without the use of large quantities of water on subirrigated plots. A good stand was obtained when only 0 to 5 cm of water were applied through the subirrigation system. Furrow planting over the subirrigation lateral will apparently be necessary in these porous soils to obtain emergence with the current placement of the laterals of 30 to 36 cm below the soil surface.

Two lots of seed were planted in the 1971 study. One lot was apparently a second generation hybrid, while the other lot was of excellent quality seed. However, the majority of the plots had poor quality seed. This was not discovered until the plants had begun to grow and silk. Many sterile stalks existed among the plots which affected yield.

Poor growth occurred during 1972. An examination of the plants showed that the root system was so poorly developed that it did not grow to the banded fertilizers. A starter band of fertilizer was applied 8 x 8 cm from

TABLE 2. PERTINENT PLANTING, PESTICIDE APPLICATIONS, AND HARVESTING INFORMATION, 1971-1974

	1971		1972			
	1st crop (all plots)	2nd crop Plots 22, 28, 32, 33	1st crop (all plots)	2nd crop Plots 6-8, 17-19, 32-34, 40-45	1973 (all plots)	1974 (all plots)
Variety	Sweet Tex 2		Bonanza		Bonanza	NK Exp 435
Planting date	June 8-10	July 21	April 13-14	Aug. 2	May 2-4	April 23-24
Rate (kg/ha)	24.6	24.6	16.8	16.8	16.8	
Replanting date	June 18-19		Plot 46 May 17			
Rate (kg/ha)	24.6		16.8			
Insecticide & application dates (Mfgs. recommended application rate used)	Sevin on July 27, Aug. 19 & 27, Parathion on July 30, Sevin on Sept. 10		Sevin + Zinc Sulfate, June 19	Sevin, Aug. 15 Sevin + Diazinon Ag 500, Aug. 24 & 29, Sept. 12 & 20	Plots 30-34 Diazinon AG 500. All plots Diazinon AG 500 June 20 & 27 Dylox July 6	
Herbicide Application dates (Mfgs. recommended application rate used)	Atrazine July 12	Atrazine Aug. 4	Atrazine April 28	Atrazine Aug. 2	Atrazine May 24-25	Atrazine May 8
Harvest date	Sept. 10	Sept. 30	Plots 1-45 July 6-7 Plot 46 July 28	Oct. 11	July 16-18	July 8-9

the seed at planting in 1973 and 1974 to assure vigorous growth immediately following emergence. Apparently adequate fertility existed on the site to establish the crop during the first year because the area had not been irrigated. The fertility was low during the following years due to heavy cropping; therefore, nitrogen at a rate of approximately 25 kg/ha was necessary for crop establishment. This was the only fertilizer applied to control plots.

Since sweet corn is a short season crop, it can be planted over a five-month period in the area. It was planted on dates between April 13 and August 2 during the four years of the study. The first year (1971) of the study, it was planted in June since much time was involved in establishing the field site. A July planting was made to see if the amount of water required to establish corn over subirrigation systems could be decreased. Two plantings were also made in 1972 to obtain further information on the newly installed subirrigation systems and to determine if the poor growth on the first crop could be circumvented through fertilization.

Insecticide applications varied from none (1974) to five in 1971 and 1972. In general, the later the crop was planted, the more insecticide applications were required. The crop was besieged at various times during the four years with fall armyworms, southwestern corn stalk borers, corn ear worms, and webworms. In some of the late plantings, the corn borers entered the plants almost as soon as they emerged, and insect control was minimal from some of the insecticide applications. It thus appears that the production of sweet corn in the area will be feasible only if it is planted early (March or April).

Excellent weed control was obtained through the use of 1.7 to 2.2 kg of Atrazine per ha each year in a post-emergence application.

Harvest dates ranged from July 8 to October 11, depending on when the crop was planted. Yield data taken for most harvests were ear number/ha, length, weight, and diameter. Only yield/ha was determined on the October 11, 1972, harvest. Yield data in the form of weight of ears/ha and number of ears/ha will be discussed in this report.

Fertilization--

Sources, rates, and application dates of various fertilizers used in the study during the four years are shown in Table 3. Methods of application have previously been noted in Table 1. All fertilizer was applied either with chisels set on 50.8-cm centers or through the irrigation systems. With the chisels on 50.8-cm centers, the fertilizer was placed 25.4 cm to the side of the plants and either 10.2 cm (above the water furrow) or 20.3 cm (below the water furrow) deep. Initially, fertilizer was injected into irrigation water with positive displacement pumps (American Meter Model Nos. 150721 and 150722, Raguse and Company, Inc., 3726 Peoria, Tulsa, Oklahoma). In later installations, a venturi injector (Model 202, Dema Engineering Company, 10020 Big Bend Boulevard, St. Louis, Missouri) was substituted for the pump.

TABLE 3. FERTILIZER SOURCES*, RATES (KG/HA) AND DATES OF APPLICATION, 1971-1974 IN KNOX COUNTY, TEXAS

Plot no.	1971	1972		1973	1974
		1st crop	2nd crop		
1	F_{11}	F_{11}		F_{11}	
2	F_6, 112.1, 5/17; 112.1, 7/26	F_6, 11.2, 5/24 22.4, 6/28		F_6, 22.4, 6/12 44.8, 6/27, 7/9	
3	F_6, 112.1, 5/17	F_6, 112.1, 5/23		F_6, 116.6, 5/30	
4	F_4, 112.1, 5/14	F_4, 123.3, 5/19		F_4, 115.5, 5/29	
5	F_2, 112.1 + 4.7 ℓ‡,6/7	F_1, 112.1, 5/22		F_1, 122.2, 5/31	
6	F_{11}	F_{11}	F_{11}	F_9, 28.0 (plots) + 32.3 (^{15}N subplots) + 38.8 NaBr, 5/5; 121.1 (plots)(5/29) + [91.5 (^{15}N subplots) + 109.7 (NaBr)] , 6/4	F_{10}, 22.4 ^{15}N subplots, 4/24; 116.6 + 82.4, 6/6
7	F_6, 112.1, 5/17; 11.2, 7/26	F_6, 11.2, 5/24 22.4, 6/28	F_6, 22.4, 7/27, 8/30, 9/18; 44.8, 10/4	F_7, 22.4, 6/12; 44.8, 6/27, 7/9; 44.8 NaBr, 6/27	F_6, 28.0, 6/5, 6/19
8	F_6, 112.1, 5/17	F_6, 112.1, 5/23	F_6, 112.1, 7/27	F_7, 116.6 + 107.6, 5/30	F_6, 111.0, 5/29
9	F_4, 112.1, 5/14	F_4, 123.3, 5/19		F_5, 115.5 + 130.0, 5/29	F_4, 112.1, 5/31
10	F_2, 112.1 + 4.7 ℓ‡,6/7	F_8, 113.2 + 134.5, 5/19		F_1, 122.2, 5/31	
11	F_{11}	F_{11}		F_{11}	F_{11}
12	F_6, 112.1, 5/17	F_6, 112.1, 5/23		F_6, 116.6, 5/30	F_7, 111.0, 5/29 113.2, 5/20
13	F_1, 112.1, 6/7	F_1, 112.1, 5/22		F_1, 122.2, 5/31	F_3, 112.1, 5/31; 113.2, 5/20
14	F_{11}	F_{11}		F_{11}	
15	F_6, 112.1, 5/17; 11.2, 7/26 8/5, 8/23, 9/2	F_6, 11.2, 5/26, 6/9; 22.4, 6/28		F_6, 22.4, 6/12; 44.8, 6/25	
16	F_4, 112.1, 5/14	F_4, 123.3, 5/19		F_4, 115.5, 5/29	
17	F_2, 112.1 + 4.7 ℓ‡,6/7	F_1, 112.1, 5/22	F_6, 112.1, 7/27	F_1, 122.2, 5/31	
18	F_{11}	F_{11}	F_{11}	F_9, 28.0 (plots) + 32.3 (^{15}N subplots) + 38.8 (NaBr), 5/5; 121.1 (plots), 5/29 + [91.5 (^{15}N subplots) + 109.7 (NaBr)], 6/4	F_{10}, 22.4 ^{15}N (subplots), 4/24; 116.6 + 82.4, 6/6
19	F_6, 112.1, 5/17; 11.2, 8/6 8/23, 8/31, 9/8	F_6, 11.2, 5/26, 6/9, 22.4, 6/21, 7/3	F_6, 22.4, 7/27 8/30; 67.3, 10/4	F_7, 22.4 + 44.8 NaBr, 6/8; 44.8 6/25, 7/9	F_6, 28.0. 6/6

continued

TABLE 3 (continued).

Plot no.	1971	1972 1st crop	1972 2nd crop	1973	1974
20	F_{4}, 112.1, 5/14	F_{4}, 123.3, 5/19		F_{5}, 115.5 + 130.0, 5/29	F_{4}, 112.1, 5/31
21	F_{2}, 112.1 + 4.7 ℓ‡, 6/7	F_{8}, 113.2 + 134.5, 5/19		F_{1}, 122.2, 5/31	
22	F_{11}	F_{11}		F_{11}	F_{11}
23	F_{6}, 112.1, 5/17	F_{6}, 112.1, 5/23		F_{7}, 116.6 + 107.6, 5/30	F_{6}, 111.0, 5/29
24	F_{6}, 112.1, 5/17	F_{6}, 112.1, 5/23		F_{7}, 116.6 + 107.6, 5/30	F_{6}, 111.0, 5/30
25	F_{1}, 112.1, 6/7	F_{1}, 112.1, 5/22		F_{1}, 122.2, 5/31	F_{3}, 111.0, 5/30 113.2, 5/20
26	F_{1}, 112.1, 6/7	F_{1}, 112.1, 5/22		F_{1}, 122.2, 5/31	F_{3}, 111.0, 5/30; 113.2, 5/20
27	F_{11}	F_{11}		F_{11}	F_{11}
28	F_{6}, 112.1, 5/17; 22.4, 9/13	F_{6}, 11.2, 5/24, 6/9		F_{6}, 22.4, 6/13; 44.8, 7/2	
29	F_{6}, 112.1, 5/17	F_{6}, 112.1, 5/23		F_{6}, 116.6, 5/30	
30	F_{4}, 112.1, 5/14	F_{4}, 123.3, 5/19		F_{4}, 115.5, 5/29	
31	F_{2}, 112.1 + 4.7 ℓ‡, 6/7	F_{1}, 112.1, 5/22		F_{1}, 122.2, 5/31	
32	†F_{11}	F_{11}	F_{11}	F_{9}, 28.0 (plots) + 32.3 (^{15}N subplots) + 38.8 (NaBr), 5/5; 121.1 (plots), 5/29 + 91.5 [(^{15}N subplots) + 109.7 (NaBr)], 6/4	F_{10}, 22.4 (^{15}N subplots), 4/24; 116.6 + 82.4, 6/6
33	F_{6}, 112.1, 5/17; 11.2†, 9/2, 9/8; 22.3, 9/13	F_{6}, 11.2, 5/26, 6/9; 22.4, 6/21	F_{6}, 22.4, 7/27, 8/30, 9/18	F_{7}, 22.4, 6/13; 44.8, 6/27, 7/10; 44.8, NaBr, 6/27	F_{6}, 28.0, 6/5, 6/19
34	F_{6}, 112.1, 5/17	F_{6}, 112.1, 5/23	F_{6}, 112.1, 7/27	F_{7}, 116.6 + 107.6, 5/30	F_{6}, 111.0, 5/29
35	F_{4}, 112.1, 5/14	F_{4}, 123.3, 5/19		F_{5}, 115.5 + 130.0, 5/29	F_{3}, 112.1, 5/13
36	F_{2}, 112.1 + 4.7 ℓ‡, 6/7	F_{8}, 113.2 + 134.5, 5/19		F_{1}, 122.2, 5/31	
37	F_{11}	F_{11}		F_{11}	F_{11}
38	F_{6}, 112.1, 5/17	F_{6}, 112.1, 5/23		F_{6}, 116.6, 5/30	F_{7}, 111.0, 5/29; 113.2, 5/20
39	F_{1}, 112.1, 6/7	F_{1}, 112.1, 5/22		F_{1}, 122.2, 5/31	F_{3}, 112.1, 5/30; 113.2, 5/20
40		F_{6}, 112.1, 5/23	F_{6}, 112.1, 7/27, 9/11; 44.8, 9/27	F_{6}, 116.6 + 107.6, 5/30	F_{6}, 111.0, 5/29

continued

TABLE 3 (continued).

Plot no.	1971	1972 1st crop	1972 2nd crop	1973	1974
41		F_6, 11.2, 5/24, 6/9, 6/27	F_6, 22.4, 7/27, 8/30, 9/11; 44.8, 9/27	F_6, 22.4, 6/7; 44.8, 6/22, 7/7	F_3, 28.0, 6/5, 6/19
42		F_{11}	F_{11}	F_{11}	F_{11}
43		F_6, 112.1, 5/23	F_6, 112.1, 7/27	F_6, 116.6, 5/30	F_6, 111.0, 5/29
44		F_6, 11.2, 5/24 22.4, 5/19, 7/3	F_6, 22.4, 7/27, 8/30, 9/11 44.8, 9/27	F_6, 22.4 + 56.0 NaBr, 6/7 44.8, 6/22, 7/7	F_6, 28.0, 6/5 6/19
45		F_{11}	F_{11}	F_{11}	F_{11}
46		F_6, 11.2, 5/26; 22.4, 6/30, 7/11		F_7, 22.4, 6/13; 44.8, 6/25, 7/9; 56.0 NaBr, 6/22	F_6, 28.0, 6/19

* F_1 - Anhydrous Ammonia

F_2 - Anhydrous Ammonia + N-Serve

F_3 Anhydrous Ammonia + Sodium Bromide

F_4 Sulfur Coated Urea

F_5 - Sulfur Coated Urea + Sodium Bromide

F_6 - Nitrogen Solution

F_7 - Nitrogen Solution + Sodium Bromide

F_8 - Sodium Nitrate + Sodium Bromide

F_9 - Sodium Nitrate + two small plots of ^{15}N-enriched Sodium Nitrate + Sodium Bromide

F_{10} - Sodium Nitrate + 1/2 of two small plots in F_9 fertilized with ^{15}N-enriched Sodium Nitrate

F_{11} - Control

† 1971 - 2nd crop -- All plots received 37 kg/ha superphosphate, 5/19.

1972 - 2nd crop -- All plots received 9.0 kg/ha Zn as zinc sulfate, 7/26, and Plots 43-45 received 38 kg/ha phosphorus as superphosphate, 7/25.
1973 - All plots received 28 kg/ha N (liquid) 5/2-4 except 6, 18, 32.
1974 - All plots received 28 kg/ha N (liquid) to all plots, 6/22-24.

‡ ℓ - liter

Particle Size Analyses and Bulk Density

Particle Size Analyzes--

During the installation of the 9.1-m access tubes, it was found that considerable variability existed in soil texture below the soil surface. Particle size analyses were then made of a number of the holes to determine the extent of this variability at the field site. Since the clay content of a soil has a major influence on solute and water movement, plots of the clay content on the two ends of the field site were graphed to show the variability that existed at the site (Figures 10 and 11). The soil ranges in clay content from 5 to 40% and is more variable in clay content below the surface than the alluvial soils in many of the irrigated valleys in the western United States. The profile is characterized by increases and decreases in clay content between the surface and the water table. This characteristic has a major influence on the soil-water retention properties of the soil profile. As pointed out by Miller (17,18), for water to move through layers with a clay content greater than depths below, an excess of water must be present in the layer of higher clay content. This in turn causes a higher soil-water potential and content than if the soil profile were uniform. This fact has implications relative to the water quality of irrigation return flows. Since the soils will retain more water than would be expected based on textural characteristics alone, more water is available for crop utilization. For those periods when crops are not growing, the soils have a "reserve" holding capacity to retain water from unscheduled rains and keep it from becoming return flow. Since such utilization of existing soil characteristics would be an economical method of keeping water from return flows, a survey of soil maps and characteristics may be worthwhile to determine the extent of layered soils in irrigated areas.

The heterogeneity of the soil precludes any possibility of using a classical model for predicting water and solute movement. As will be discussed later, an empirical approach was developed.

Bulk Density--

Bulk density, as well as soil texture, may influence movement of water and solutes. Bulk density was determined with a calibrated density probe (Model 1351, Troxler Electronic Laboratories, Inc., Research Triangle Park, North Carolina) on all access probe holes on the field site. Bulk densities of the north end of the main field site are graphed in Figure 12. As would be expected, the bulk density was quite variable. In general, bulk density increased with depth from 1.40 to 1.55 at the surface to 1.70 to 1.90 at 7.6 m. However, there were high density and low density "pockets" located throughout the profile. It would be expected that this variability in bulk density would have a definite effect on water and solute movement.

As will be discussed later, bulk density had a definite effect on the soil-water content values. It was therefore necessary to correct the soil-water content values for bulk density.

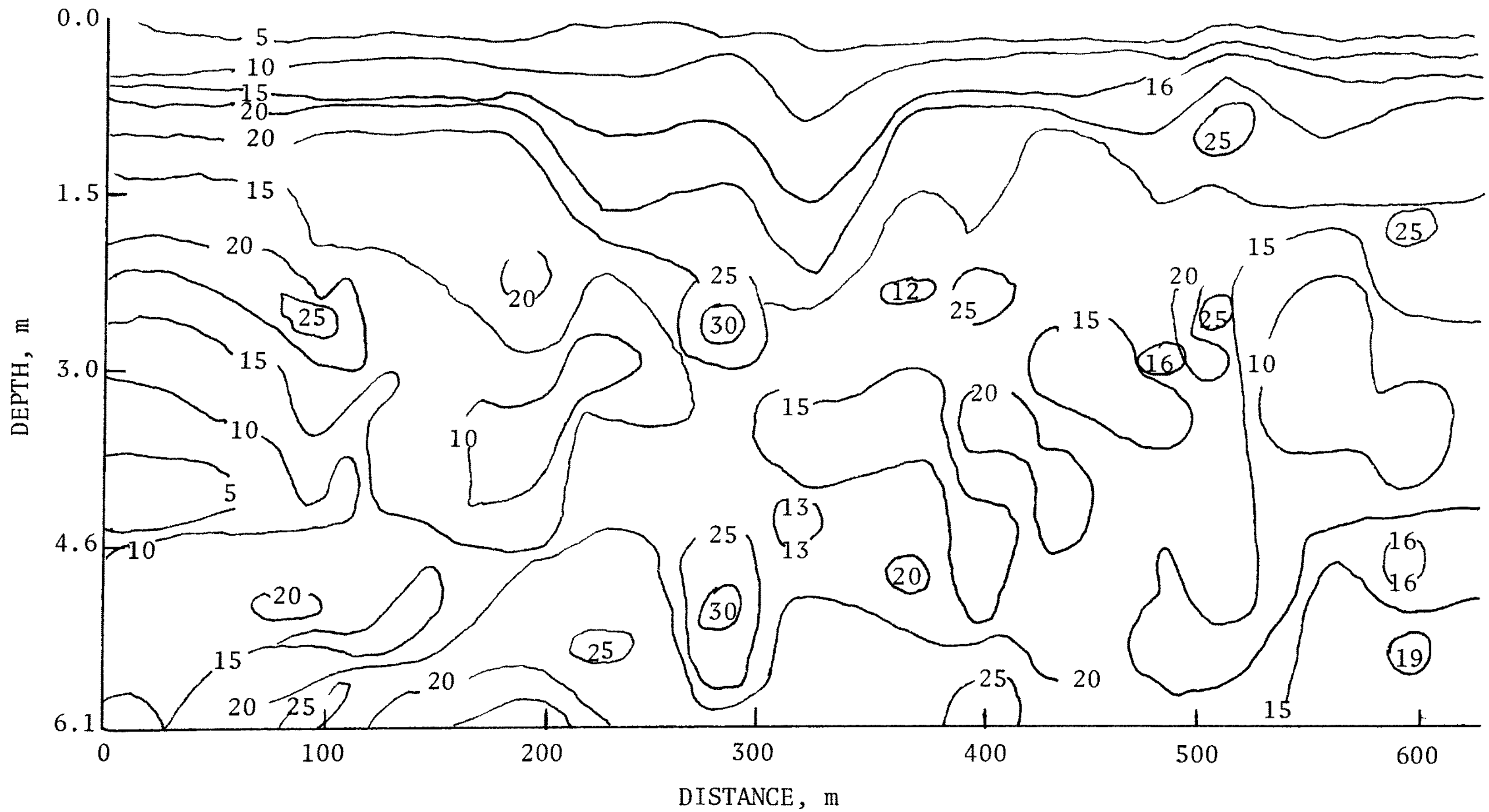


Figure 10. Clay content between the surface and the water table at the south end of the water quality research site at Munday, Texas.

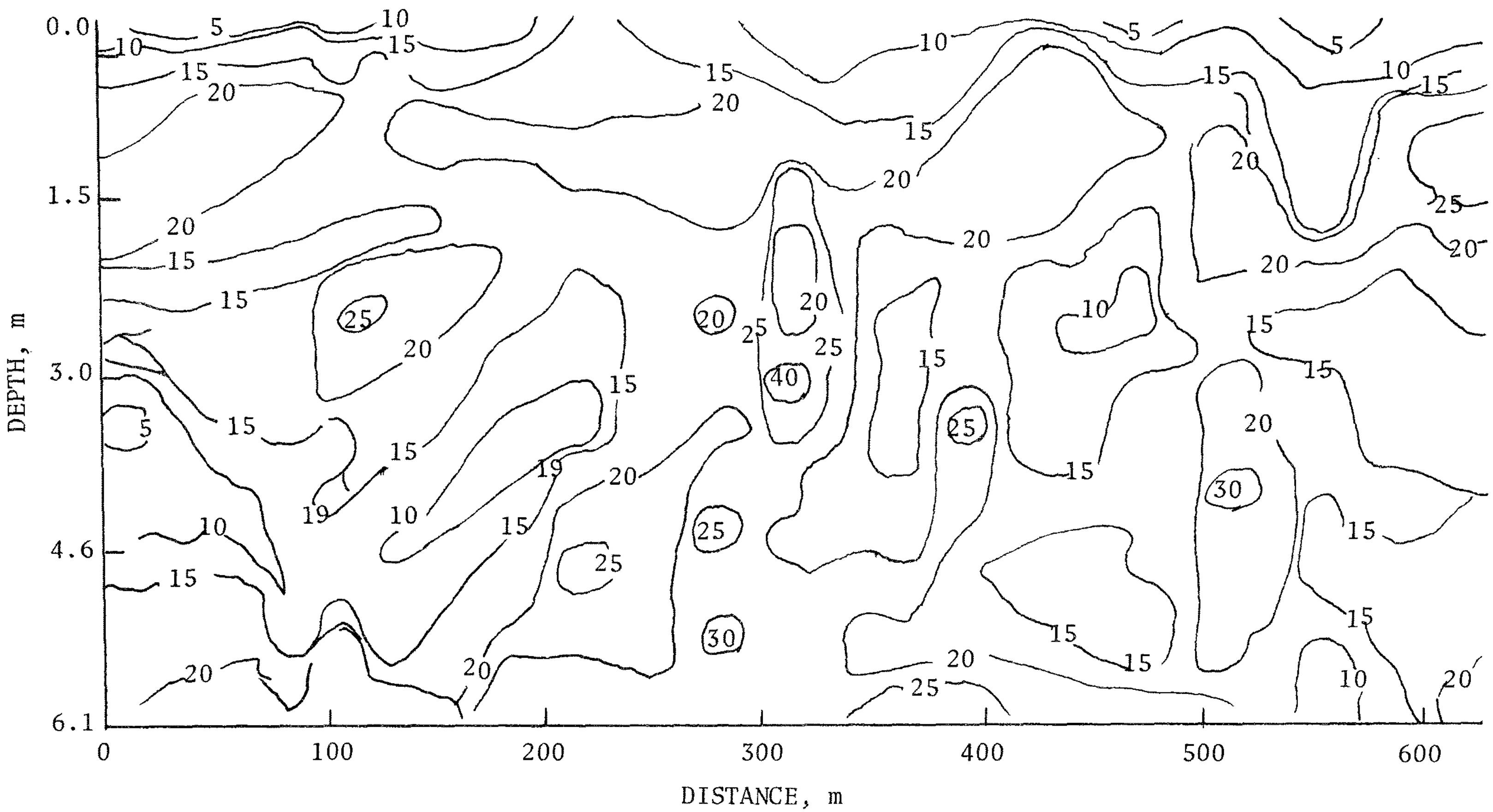


Figure 11. Clay content between the surface and the water table at the north end of the water quality research site at Munday, Texas.

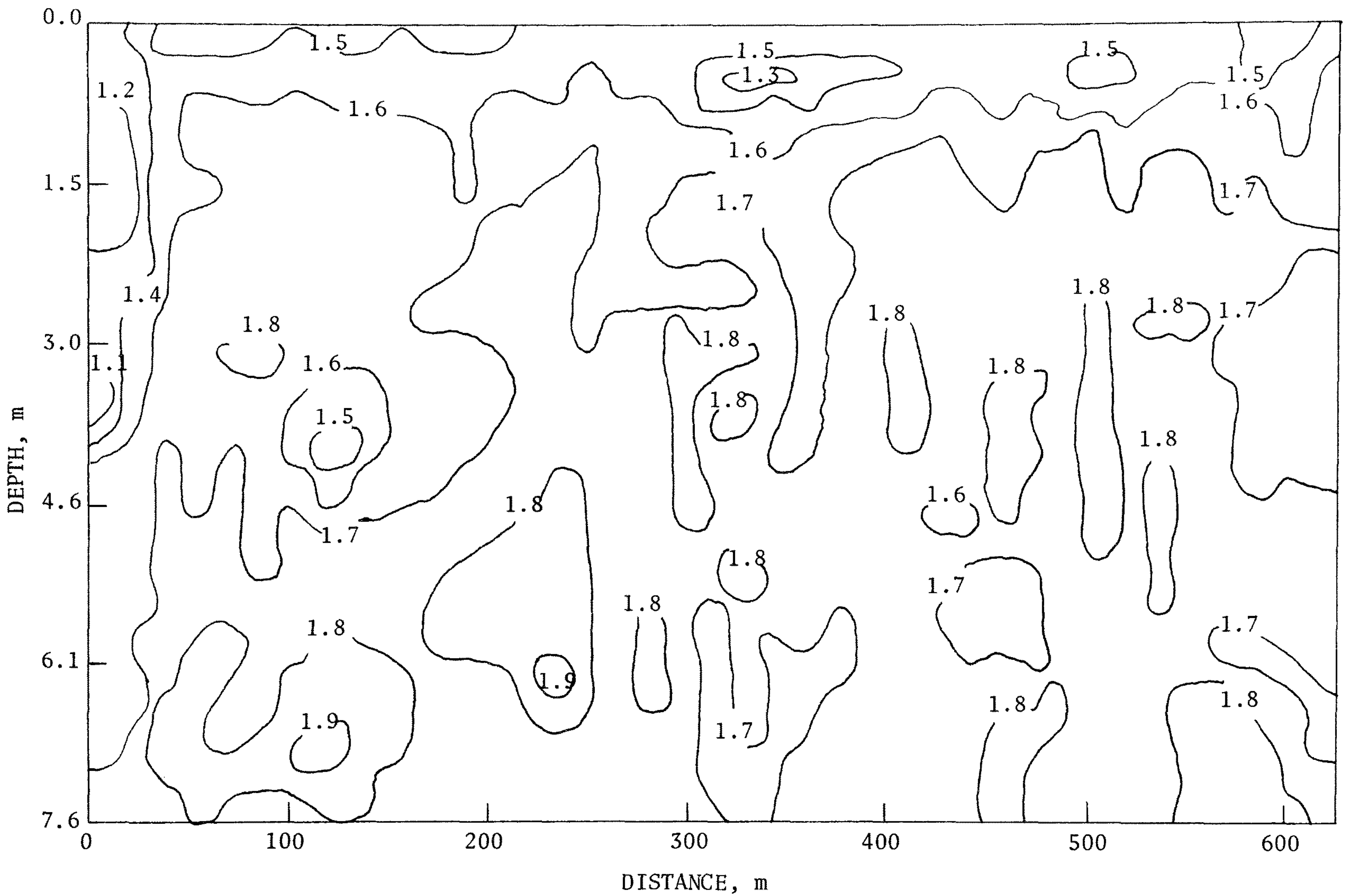


Figure 12. Bulk density between the surface and the water table of the north end of the field site, Munday, Texas.

Irrigation

Systems--

As previously discussed, there was some problem in obtaining emergence over the subirrigation system the first year (1971) when the crop was planted on the bed rather than in the furrow. However, this was a problem with planting rather than the irrigation system itself. In general, the systems performed without problems the first year of the study. The 1.8-m risers on the sprinkler system were found to be undesirable for corn in the early stages of growth. These were reduced to 0.9-m risers prior to the initiation of the 1972 growing season. This reduced drift and possibly evaporation losses during the early part of the growing season.

The manual subirrigation system was besieged with minor problems. Most of these were water leaks found during flushing of the system prior to the growing season. Several control valves had frozen and split during the winter months. Almost all pressure gauges had to be replaced. Many leaks occurred in the laterals during the growing season due to gophers eating holes in the polyethylene pipe. A rodent repellent was applied through the system to the plots where the gophers did the most damage. Other leaks found in the laterals were due to splitting of the pipe around connectors where it had been repaired once before. Some stoppage of orifices occurred. The filters were changed only at the beginning of the growing season.

A few problems occurred with the automation in the automated subirrigation system. These were associated with vacuum switches on the switching tensiometers and the solenoid valves. The vacuum switches were replaced with a switching-type tensiometer gauge manufactured by Irrometer Company. Satisfactory operation occurred thereafter.

Sand passed through the 350 μ filter and plugged the orifice in the diaphram of the solenoid valves. This problem was solved by replacing the 350 μ filters with 100 μ filters. It was necessary to replace these filters three times during the growing season even though they were washed periodically. Other solenoid valve trouble occurred due to the corrosion of the brass interior which caused the diaphram to remain closed when the valve was activated. This problem was solved by periodically applying a thin coat of vacuum stopcock grease to the sides of the diaphram and interior wall of each valve. Poor connections in electrical plugs exposed to the weather created minor problems.

The only problem with the trickle irrigation system was external plugging of the orifices. This was primarily due to sand blowing into the orifice outlet and crusting while the system was not operating. Other plugging occurred due to algae growth in the orifices.

Plugging also occurred in the subirrigation systems. The automated subirrigation systems used in this study (Plots 40 through 45) were installed in 1972. In 1973, individual plants were observed to be water-stressed, indicating the presence of plugged emitters. Each of the six plots consisted of 16 laterals with approximately 73 emitters per lateral.

These were Whitney orifices (manufactured by Submatic, Inc., 709 27th St., Lubbock, Texas) with a 0.56-mm diameter opening.

The number of plugged emitters in each lateral in each plot was estimated from the locations of water-stressed plants. Plugged emitters were excavated, removed from the lateral, and inspected to determine the cause of plugging. Then four entire laterals in Plot 40 were unearthed to determine the number of plugged orifices which were not located by plant inspection.

Two causes of plugging were observed. Orifices were plugged by root hairs and by sand particles. The number of plugged emitters located in each plot by plant inspection was multiplied by the ratio of total plugged emitters to plugged emitters determined by plant inspection in Plot 40 to obtain an estimate of total number of plugged emitters in each plot. These values are given in Table 4. An average of 5% of the emitters were plugged by sand and 7% by roots. Twelve percent of all emitters were plugged after one season of use.

TABLE 4. PERCENT OF EMITTERS IN AUTOMATED SUBIRRIGATION PLOTS PLUGGED AFTER ONE SEASON OF USE

Plot	Percent plugged		
no.	By sand	By roots	Total
40	8	15	23
41	4	10	14
42	4	4	8
43	8	4	12
44	4	4	8
45	4	2	6
Avg.	5	7	12

Water Applied at Each Irrigation--

A summary of the amounts of irrigation water applied at each irrigation to the different plots is given in Table 5. During the first year of the study (1971), 7.6 cm were applied to the sprinkler- and furrow-irrigated plots per irrigation and only 5.0 cm were applied to the subirrigated plots per irrigation using the criteria stated in Table 5. The reason these amounts were used was that 7.6 cm was the amount required to obtain good distribution on the furrow-irrigated plots. Based on the preliminary work with distribution of water from the subirrigation system, 5.0 cm appeared to be adequate to return the root zone to field capacity.

It was obvious that these were poor criteria for scheduling irrigations. Therefore, in the remaining years the amounts of water added were based on potential ET with the amounts added being variable except for the furrow irrigation systems where a 7.6-cm minimum was required to obtain good distribution. Another exception was in 1974 when two and three times potential ET were added to determine the influence on ion movement. In

TABLE 5. SUMMARY OF THE AMOUNTS OF WATER APPLIED AT EACH IRRIGATION TO THE DIFFERENT PLOTS AT THE FIELD SITE NEAR MUNDAY, TEXAS, 1971-1974

Year	
1971	Plots 1-13 (sprinkler-irrigated) and Plots 14-26 (furrow-irrigated) received 7.62 cm and Plots 27-39 (subirrigated) received 5.08 cm when leaf curl or designated potential level occurred.
1972	Plots 1-39 received 2.54- to 7.62-cm irrigations with the actual amount being a percentage of potential ET based on stage of growth (LAI) when leaf curl or designated potential level occurred.
	Plots 40-45 (automatically subirrigated) and Plot 46 (automatically drip-irrigated) received 0.23- to 1.45-cm irrigations with the actual amount being that required to lower the potential below the preset level of the switching tensiometer.
1973	Plots 1-39 received 3.68- to 8.00-cm irrigations with the actual amount based on the criteria used in 1972.
	Plots 40-46 received 0.03- to 1.88-cm irrigations with the actual amount based on the criteria used in 1972.
1974	Plots 6, 7, 11, 18, 19, 22, 24, 32, 33, and 37 received 2.92- to 10.54-cm irrigations with the actual amount based on the criteria used in 1972.
	Plots 8, 12, 19, 25, 34, and 38 received 5.08- to 16.26-cm irrigations with the actual amount based on two times the criteria used in 1972.
	Plots 9, 13, 23, 26, 35, and 39 received 5.08- to 20.57-cm irrigations with the actual amount based on three times the criteria used in 1972.
	Plots 40-46 received 0.08- to 3.73-cm irrigations with the actual amount based on the criteria used in 1972.

practice, not quite three times potential ET were added because the amount of water required was unrealistic from a practical standpoint.

The amounts added at each irrigation through the automated systems were usually less than 2.5 cm. It should be pointed out that although the potential levels were preset on the switching tensiometers between -20 to -40 cb, varying according to the year, the potential increased approximately -10 cb above the preset level due to the lag in the time required for the water to move from the orifices in the irrigation systems to the tensiometer. As will be discussed later, these frequent small amounts were a factor in creating some extremely high irrigation water-use efficiencies. However, it should also be pointed out that these relatively constant high moisture levels apparently caused problems with roots growing into the orifices of the subirrigation systems.

Water Applied Prior to Emergence--

The amounts of water applied prior to crop emergence are given in Table 6. The amounts ranged from 0 to 20.3 cm. As previously discussed, the largest amount was required to obtain emergence of corn planted on the bed over a subirrigation system on the second planting in 1971. A subsequent second planting in the same year required only 2.5 to 5.0 cm to obtain emergence.

TABLE 6. AMOUNTS OF WATER APPLIED PRIOR TO EMERGENCE TO THE DIFFERENT PLOTS AT THE FIELD SITE NEAR MUNDAY, TEXAS, 1971-1974

Year	Plot no.	Planting	Amount, cm
1971	1-13	1st	7.62
		2nd	5.08
	14-26	1st	7.62
		2nd	6.35
	27-39	1st	7.62
		2nd	20.32
	27, 28, 32	3rd	5.08
	33		2.54
1972	1-13	1st	None
	14-26		7.62
	27-36		None
	37-39		5.08
	40-45		2.54
	46		1.27
	6-8, 17-19, 32-34	2nd	7.62
	40-41		4.75
	42		4.67
	43-45		4.62
1973	1-46		None
1974	6-9, 11-13, 18-20 22-26, 32-45		5.08

In 1972, no water was applied prior to emergence in the sprinkler-irrigated and most of the subirrigated plots at the first planting. Amounts of 4.6 to 7.6 cm were required to obtain emergence on the second planting. No water was applied to obtain emergence in 1973, and 5.0 cm were applied in 1974.

In summary, the amount of irrigation water required to obtain good crop emergence varied between years. These soils are self-mulching and will store adequate moisture for planting for several months. If water is not available to be stored, approximately 5.0 cm are adequate to obtain crop emergence.

Water Applied During Growing Season--

The amounts of water applied during the growing season are given in Table 7. If the average amounts applied through the sprinkler and manual subirrigation systems are compared to the furrow systems, one can see that the sprinkler and subirrigation systems were consistently superior following the first year of the study when water applications were based on amounts rather than potential ET and leaf area. In 1971, the sprinkler system had the greatest amount applied (35.8 cm) followed by the furrow (30.1 cm) and manual subirrigation systems (17.8 cm). The furrow system had the greatest average amount applied in 1972 (22.1 cm) followed by the subirrigation (18.4 cm) and the sprinkler system (16.6 cm). The furrow irrigation system had the greatest amount applied in 1973 (35.2 cm), while the sprinkler and subirrigation systems were equal in the average amount applied (24.8 cm). In 1974, the greatest average amount was applied through the furrow irrigation system (32.2 cm) followed by the manual subirrigation system (27.1 cm) and the sprinkler irrigation system (26.0 cm). These data suggest that little difference exists among manually-operated systems relative to irrigation water-use efficiency if scheduling is done on the basis of potential ET and the system is designed so that adequate distribution can be obtained. It was not possible to apply only the amounts based on potential ET and leaf area through the furrow system due to the porosity of the soil at the site.

Significantly less irrigation water was required by the automated irrigation systems with the average amounts required ranging from 10.9 to 16.7 cm or almost 50% less than using manual systems and irrigating on the basis of potential ET or set amounts using stage of growth or water potential as a criteria for applying water. These significant differences will be discussed in detail in a later section.

Soil Water Potential

During the first year of the study, no problems were encountered with the tensiometers in measuring soil-water suction. They were read three to six times weekly at 0.13 to 1.27 m and weekly at 1.27 to 2.54 m.

Many of the tensiometer gauges were inoperable at the beginning of the 1972 season due to freezing in storage. After the gauges were replaced, the tensiometers functioned without problems. All of the tensiometers were read three times weekly and serviced at least once every two weeks. Some of the shallow depth tensiometers (0.13 to 0.26 m) had to be serviced more frequently. Since adequate soil data were obtained in 1971 and 1972 on soil-water suction at Location 2, all but the 0.13, 0.25 and 0.38 m

TABLE 7. AMOUNTS OF WATER APPLIED (CM) DURING THE GROWING SEASON TO THE DIFFERENT PLOTS AT THE FIELD SITE NEAR MUNDAY, TEXAS, 1971-1974

	Plot no.													
Year	1	2	3	4	5	6 1st*	7 1st	8 1st	9	10	11	12	13	1st crop, avg
1971	22.86	30.48	22.86	53.34	30.48	45.72	53.34	38.10	53.34	38.10	25.40	25.40	25.40	35.76
1972	20.32	20.96	27.94	29.21	27.94	20.32	20.96	20.32	29.21	21.59	20.32	27.94	27.94	24.23 (16.61 if 7.62 cm required for sampling is eliminated)
1973	21.97	25.53	20.32	25.53	22.48	25.65	25.65	25.53	25.65	25.53	25.65	26.42	26.42	24.79
1974						25.40	24.89	58.04	70.92		27.81	58.04	74.80	48.56 (All plots)
														26.03 (Plots irrigated on basis of potential ET)
						2nd*	2nd	2nd						
1972						5.08	11.43	5.08						

Year	14	15	16	17 1st	18 1st	19 1st	20	21	22	23	24	25	26	1st crop, avg
1971	38.10	30.48	30.48	22.86	30.48	53.34	38.10	45.72	20.32	20.32	20.32	20.32	20.32	30.09
1972	17.78	17.78	25.40	25.40	10.16	22.86	25.40	27.92	22.86	22.86	22.86	22.86	22.86	22.08
1973	38.10	38.10	38.10	30.48	38.10	38.10	30.48	38.10	31.17	32.05	34.82	34.82	34.82	35.18
1974					30.96	30.48	49.53		29.08	53.85	38.10	50.04	61.72	42.98 (All plots)
														32.15 (Plots irrigated on basis of potential ET)
				2nd	2nd	2nd								
1972				15.24	5.08	10.16								

Year	27 1st	28 1st	29	30	31	32 1st	33 1st	34 1st	35	36	37	38	39	1st crop, avg
1971	7.62	7.62	12.70	17.78	15.24	5.08	7.62	22.86	33.02	35.56	20.32	22.86	22.86	17.78
1972	20.32	15.88	27.94	27.94	31.75	20.96	24.77	24.13	31.75	36.83	25.40	33.02	33.02	27.20 [18.40 if water required for sampling (7.62 cm) and crop establishment (5.08 in plots 37, 38, 39) are eliminated]
1973	20.57	20.57	25.65	22.48	22.48	25.65	26.29	25.65	25.65	28.30	26.29	26.42	26.40	24.80
1974						25.53	26.42	42.42	44.70		29.41	56.52	57.66	40.39 (All plots)
														27.12 (Plots irrigated on basis of potential ET)
	2nd	2nd				2nd	2nd	2nd						
1971	5.08	5.08				5.08	11.43							
1972							6.35	10.16						

Year	40 1st	41 1st	42 1st	43 1st	44 1st	45 1st	46	1st crop, avg
1971								
1972	17.17	13.16	10.54	8.74	8.31	9.07	9.30	10.90
1973	13.34	13.18	18.75	12.95	12.65	13.28	15.24	14.20
1974	17.78	15.54	15.70	11.23	15.75	9.12	31.65	14.20 (Excluding Plot 46)
1974								16.68 (Including Plot 46)
	2nd	2nd	2nd	2nd	2nd	2nd		
1972	11.96	4.19	5.51	10.49	10.49	7.32		

*Crop for year indicated

tensiometers were removed from this location prior to the 1973 growing season. Tensiometers were removed from plots not used in 1974.

Specific relationships of soil-water potential and irrigation return flow will be discussed later in the report. Therefore, only generalities will be discussed at this time. Figure 13 shows the depth potential relationships of plots from the sprinkler irrigation, furrow irrigation, subirrigation and automated subirrigation systems. Both the matric and total potentials are shown along with the clay content at the different depths. It can easily be seen that the greatest change in potential for all irrigation systems occurred at 15 cm and varied from -70 to 0 cb total potential. In the sprinkler, furrow, and manually-subirrigated plots, there was considerable change at 30 cm with the range being -52 cb to -2 cb, -57 to -2 cb, and -35 to 0 cb, respectively. The automated subirrigation plot only fluctuated from 0 to -10 cb during the year. This was the depth at which the switching tensiometer was located in the soil, and it appears that the potential remained fairly constant at this depth. The amount of fluctuation at 46 cm was least in the sprinkler-irrigated plots (-6 to -8 cb) followed by the manual subirrigated plots (-4 to -8 cb), automated subirrigated plots (-3 to -10 cb) and furrow-irrigated plots (-6 to -18 cb). Fluctuation between 46 cm and 1.5 m was greatest in the subirrigation plots, intermediate in the furrow-irrigated plots, and least in the sprinkler-irrigated plots. These trends generally held true for all plots in each system. More water was used from the lower zones in subirrigation systems than in the furrow systems. The least amount of water was used between 46 cm and 1.5 m in the sprinkler system. In general, there was little difference (<10 cb) in the change in potential between the plots of the different irrigation systems below 1.5 m. The exception was the sprinkler-irrigated plot at 2.4 m which increased from -36 cb to -18 cb. This appeared to be a relatively dry zone which increased in potential as water was added.

Texture had a major influence on the potential curves. Generally, the potential was greater in zones of lower clay content that were immediately above zones of higher clay content; i.e., 1.8 m vs 2.1 m in the sprinkler-irrigated plot, 2.4 m vs 2.7 m in the furrow-irrigated plot, 1.5 m vs 2.1 m in the manual subirrigated plot, and 1.2 m vs 1.8 m in the automatically-subirrigated plot. The potential at "field capacity" was -10 cb or greater in these zones, suggesting that this is a characteristic common to layered soils. If this is true, these soils hold more water than one would normally expect from the commonly accepted -33 cb value. This characteristic could be of value in maintaining the quality of irrigation return flows in that it extends the previously reported range of potential from -33 cb to -10 cb, allowing more water to be stored in the soil profile before significant drainage occurs. There was a trend for the potential gradient to increase down from 46 cm to 3.0 m. However, there were exceptions to this (2.4 m in the sprinkler-irrigated plots, 1.5 and 2.4 m in the furrow-irrigated plots, 1.5 and 3.0 m in the manual subirrigated plots, and 1.2, 1.8 and 3.0 m in the automatically-subirrigated plots). In general, these zones were in or immediately above the zones of highest clay content. The textural influences will be discussed in more detail under the section on hydraulic conductivity (K). As would be expected, there was an upward gradient

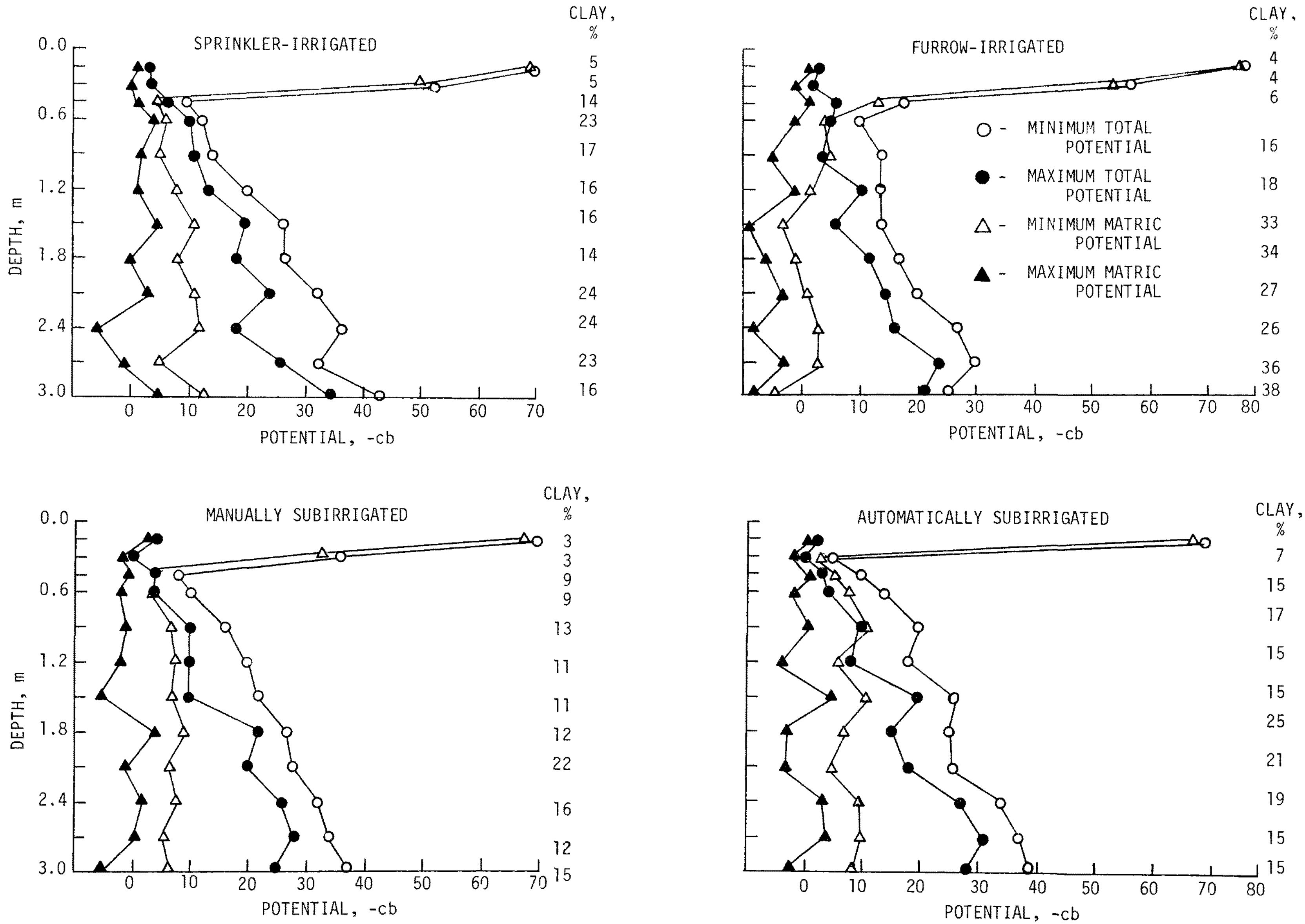


Figure 13. Maximum and minimum total and matric potential-depth curves and clay percentage of selected plots in the various irrigation systems.

between 15 and 46 cm and the surface due to the evaporative demand of the atmosphere and crop use.

Soil-Water Content

As previously mentioned, 5.08-cm diameter access tubes were installed at two locations to 9.1 m in each plot to obtain soil-water content readings. Data were taken at 0.30-m increments periodically in each plot where possible. In some plots the tubes were bent and in others the welded caps on the bottom had leaks so that water from the water table entered the tube making it impossible to obtain readings for the full depth.

Calibration of Neutron Probes--

In this section only general observations concerning water content will be made. During the first year of the study, the neutron probes were not calibrated, therefore only relative changes in soil-water content were measured. During the second year of the study, standards were constructed by packing soils of various textures and moisture contents obtained at the site to different bulk densities. Figures 14 and 15 show the moisture-count ratio curves obtained for the two probes used in the studies. Figures 16 and 17 show the relationship between moisture content (θ)/count ratio (CR) and bulk density for the two probes.

Figure 18 shows the relationship between counts and wet density of all soil textures for the density probe used in the study. It is interesting to note that textures did not influence the counts at a particular bulk density and that the relationship between wet density and counts was good for all textures (r - 0.9815).

Comparison of Corrected and Uncorrected Soil-Water Content Values for Troxler Neutron Probe--

Figure 19 shows the relationship between the values for θ using the standard curve from the manufacturer of the neutron probe and values for θ using the curves developed from standards made from soils at the site. It can be readily seen that there is a major difference between the values for θ obtained using the two curves. The uncorrected values are higher than the corrected values by 1 to 16% by volume. The differences between the corrected and uncorrected values increased with depth. Maximum difference at the high moisture content was 10% by volume and at the low moisture content 16% by volume. This suggests that the error was greater at lower values of soil-water content than at higher values of soil-water content. As will be discussed later, the ability to detect these differences is very important.

A comparison of the uncorrected differences indicates that the value differences were small between the maximum and minimum soil-water content below 1.5 m (<1% by volume) while differences in corrected values were 2 to 5% by volume. This indicates that the uncorrected readings were less sensitive to changes than the corrected readings. The sensitive values were more desirable for evaluating predictive models.

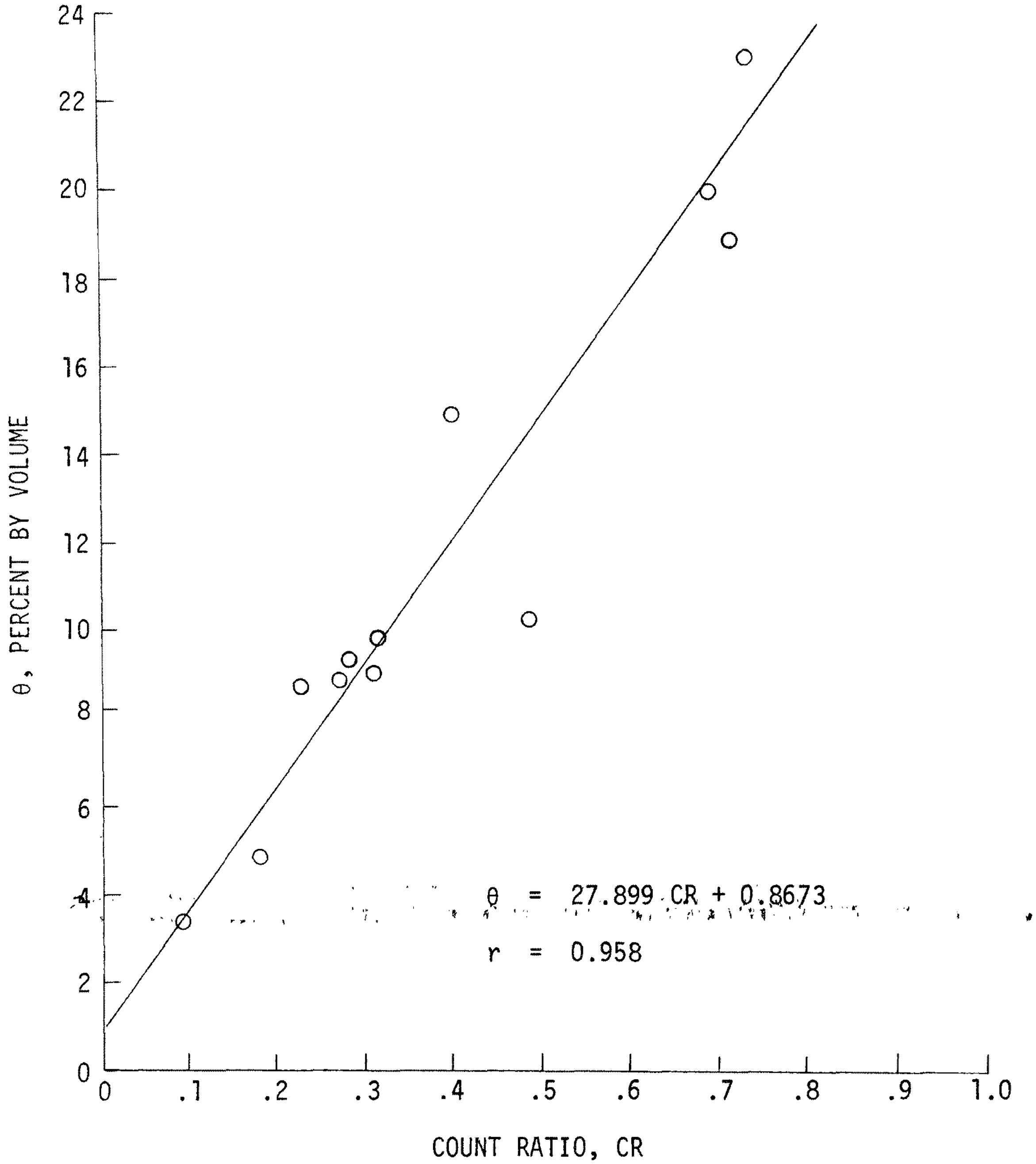


Figure 14. Relationship between θ and count ratio for Troxler neutron moisture probe No. 1 used at the field site near Munday, Texas.

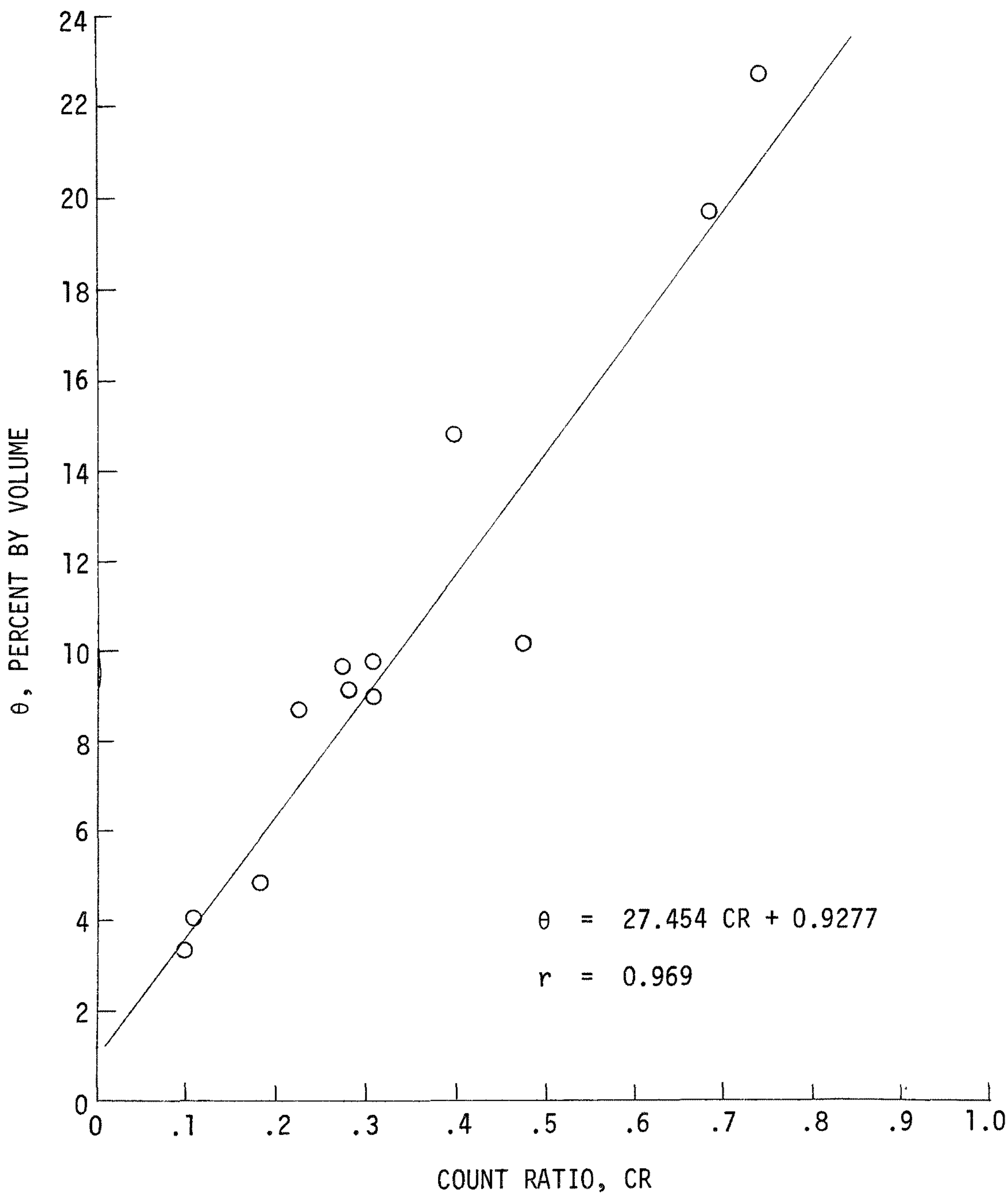


Figure 15. Relationship between θ and count ratio for the Troxler neutron probe No. 2 used at the field site near Munday, Texas.

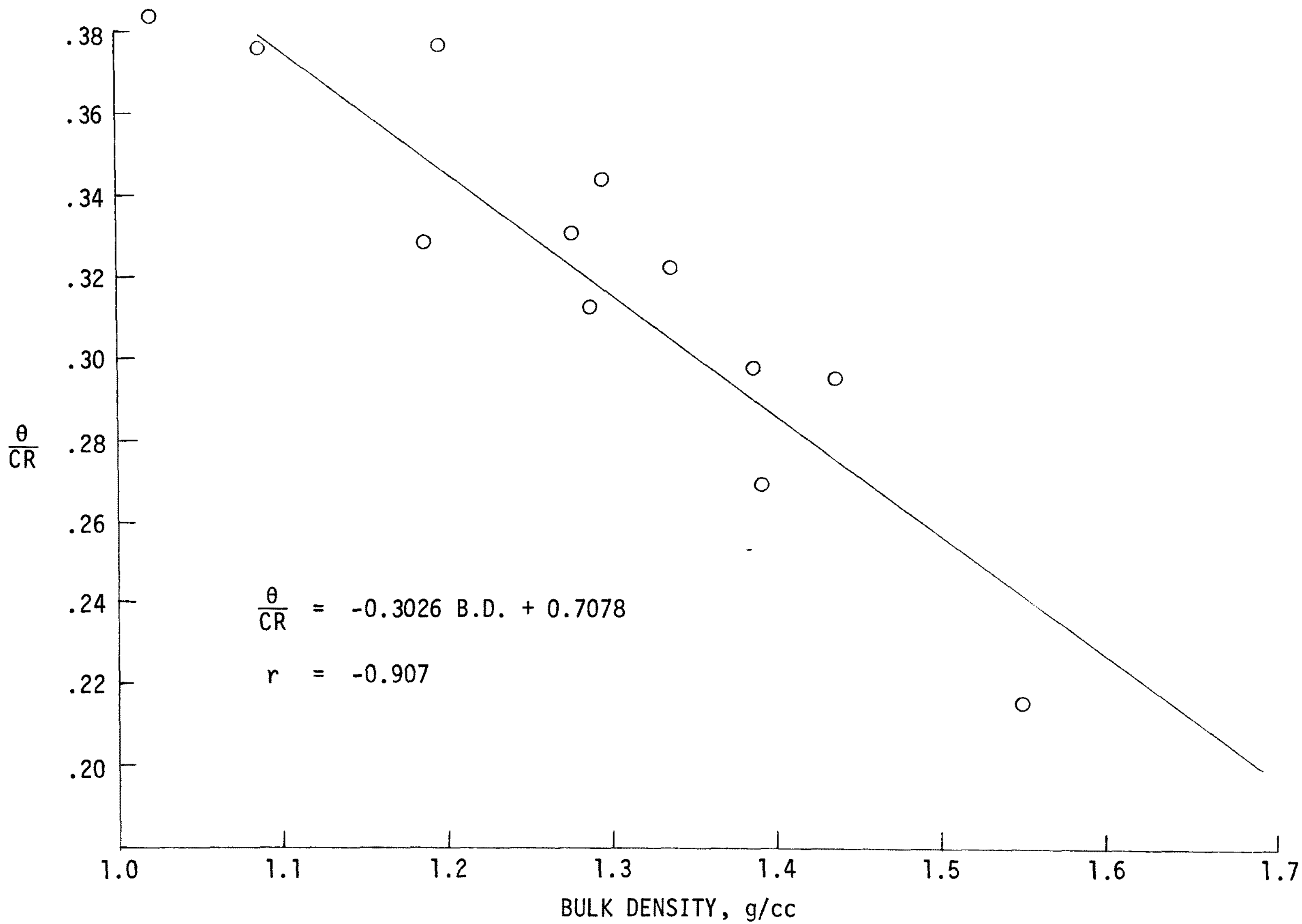


Figure 16. Relationship between θ/count ratio and bulk density for Troxler neutron probe No. 1 used at the field site near Munday, Texas.

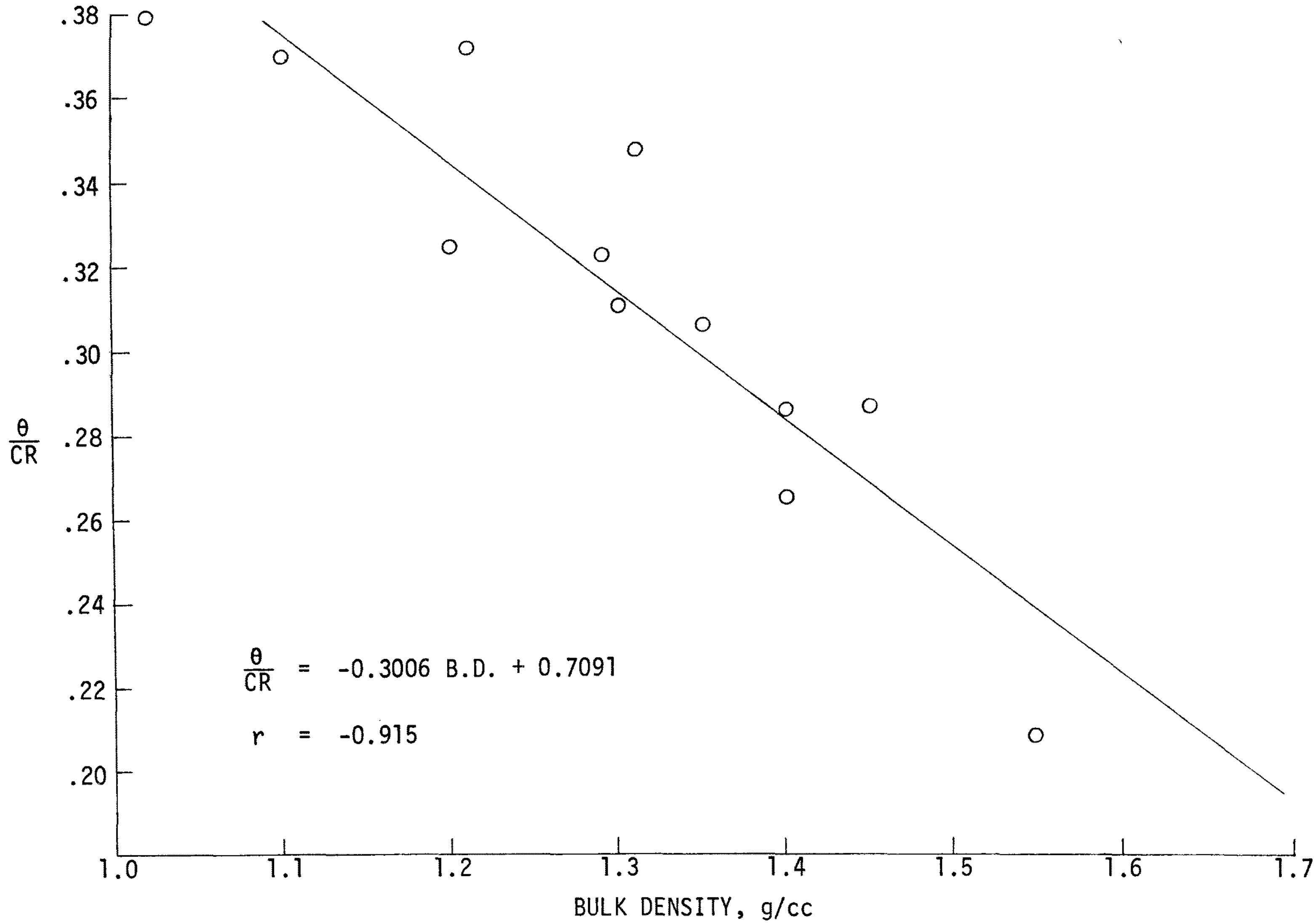


Figure 17. Relationship between θ/count ratio and bulk density for Troxler neutron probe No. 2 used at the field site near Munday, Texas.

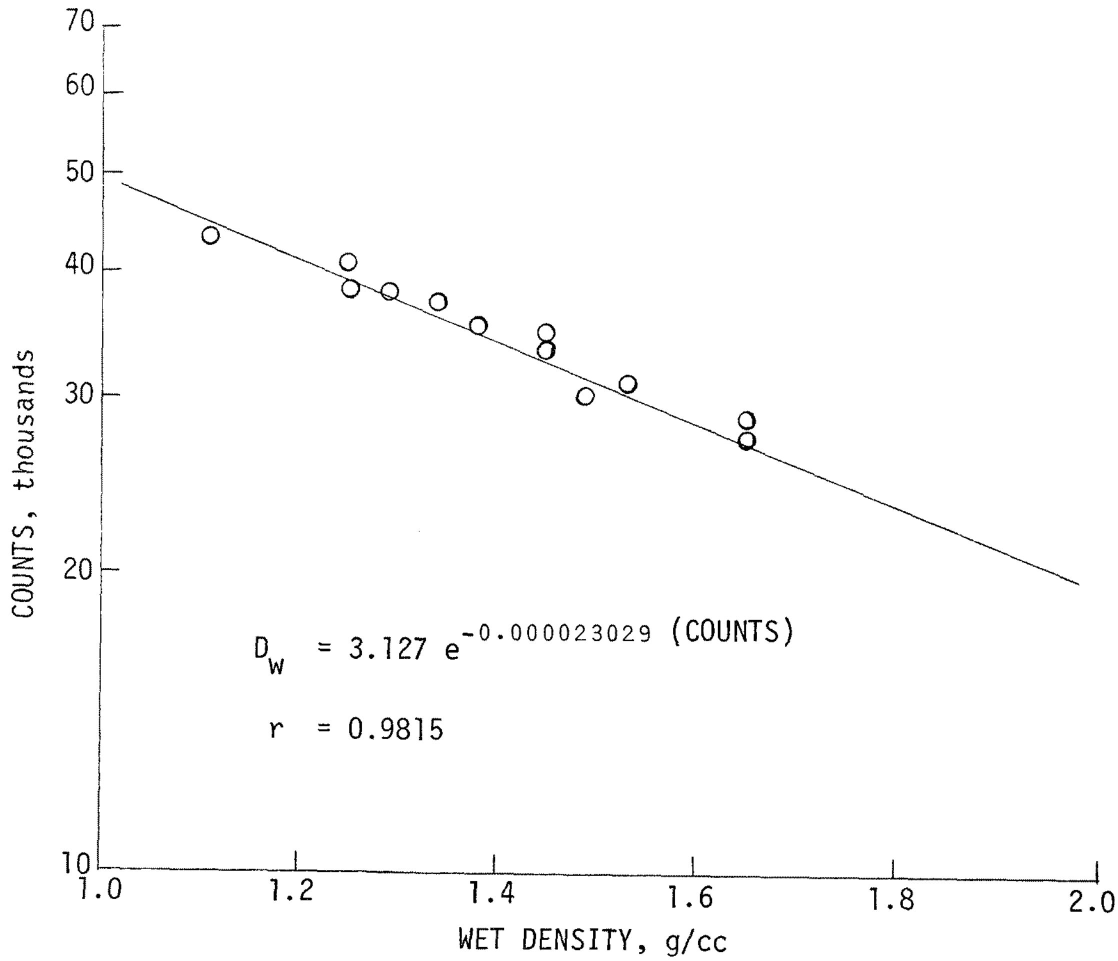


Figure 18. Relationship between counts and wet density for the Troxler density probe used to determine the bulk densities of the field site near Munday, Texas.

Comparison of Troxler and Well Reconnaissance Probes--

The characteristics of the standards used to calibrate the neutron probes are shown in Table 8. In addition to the two Troxler probes, a probe manufactured by Well Reconnaissance, Inc., on loan from the U. S. Environmental Protection Agency, was also calibrated. Figure 20 shows the relationship between θ from the standards and the meter readout of the probe. It can be seen that the texture had no influence on the relationship. The high R value indicates that a good relationship existed between the two parameters. A better relationship would probably have been obtained if more data had been available.

Figure 21 shows the relationship between θ (standards)/θ (Reconnaissance probe) vs bulk density. Although there was an effect due to density, it was not as pronounced as with the Troxler probes (Figures 16 and 17). However, there was a definite influence due to bulk density. Table 9 compares values obtained using the Company standards and constructed

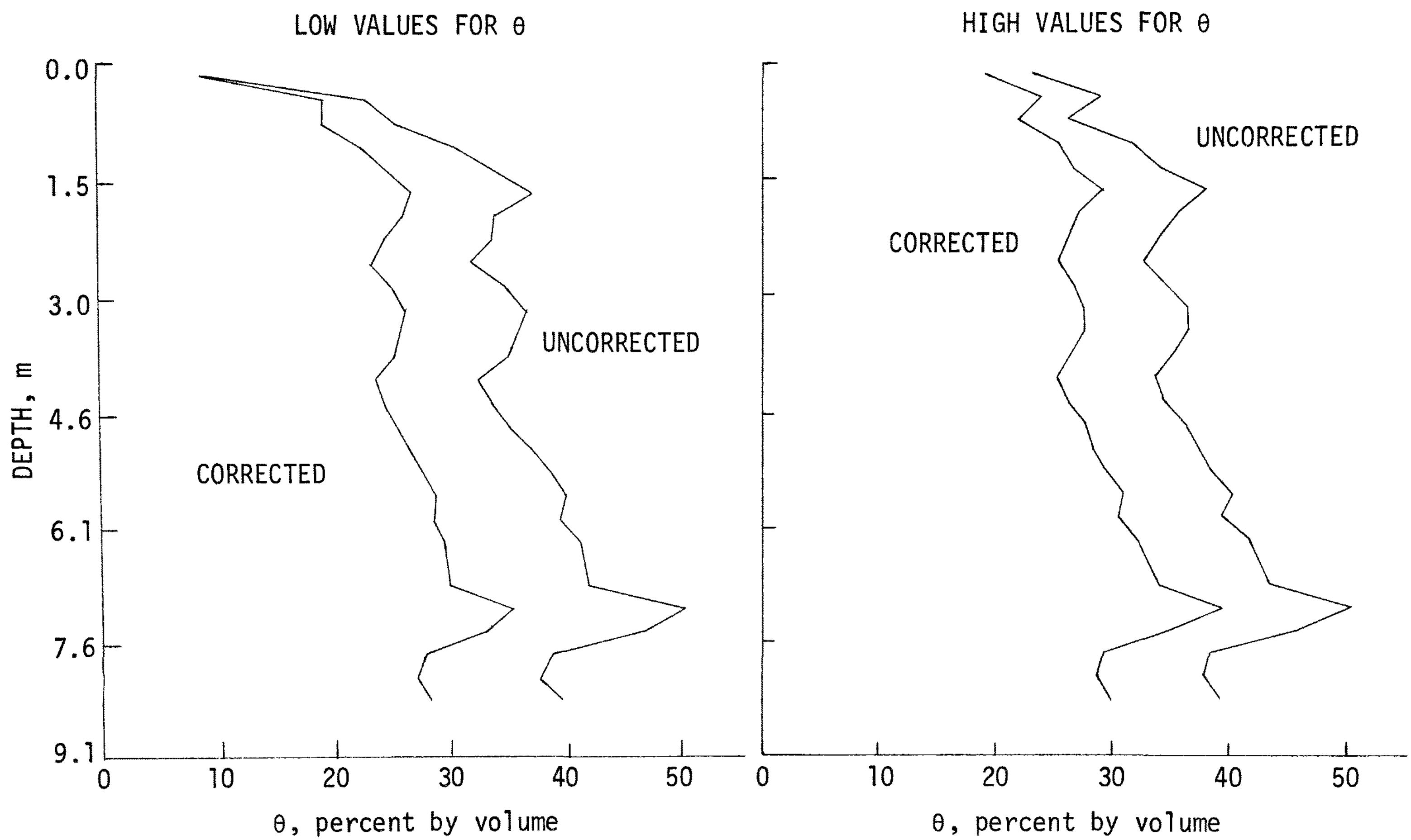


Figure 19. Comparison of uncorrected values for θ using the standard curve from the Company and corrected values for θ using the curve developed from standards made of soils at the site having different bulk densities.

TABLE 8. CHARACTERISTICS OF STANDARDS USED TO CALIBRATE NEUTRON PROBES

Standard number	Particle size, % Sand	Silt	Clay	Bulk density, g/cm^3	Wet density, g/cm^3	Moisture content, % by volume
1	42	35	23	1.21	1.25	4.05
2	42	35	23	1.40	1.45	4.82
3	42	35	23	1.02	1.11	8.70
4	42	35	23	1.29	1.38	9.18
5	42	35	23	1.10	1.25	14.87
6	42	35	23	1.30	1.53	22.88
7	60	20	20	1.20	1.39	18.80
9	60	20	20	1.21	1.24	3.44
10	60	20	20	1.20	1.29	8.85
11	60	20	20	1.40	1.49	9.00
12	76	13	11	1.31	1.34	3.38
13	76	13	11	1.45	1.65	19.88
14	76	13	11	1.61	1.81	19.78
15	76	13	11	1.35	1.45	9.80
16	76	13	11	1.55	1.65	10.20

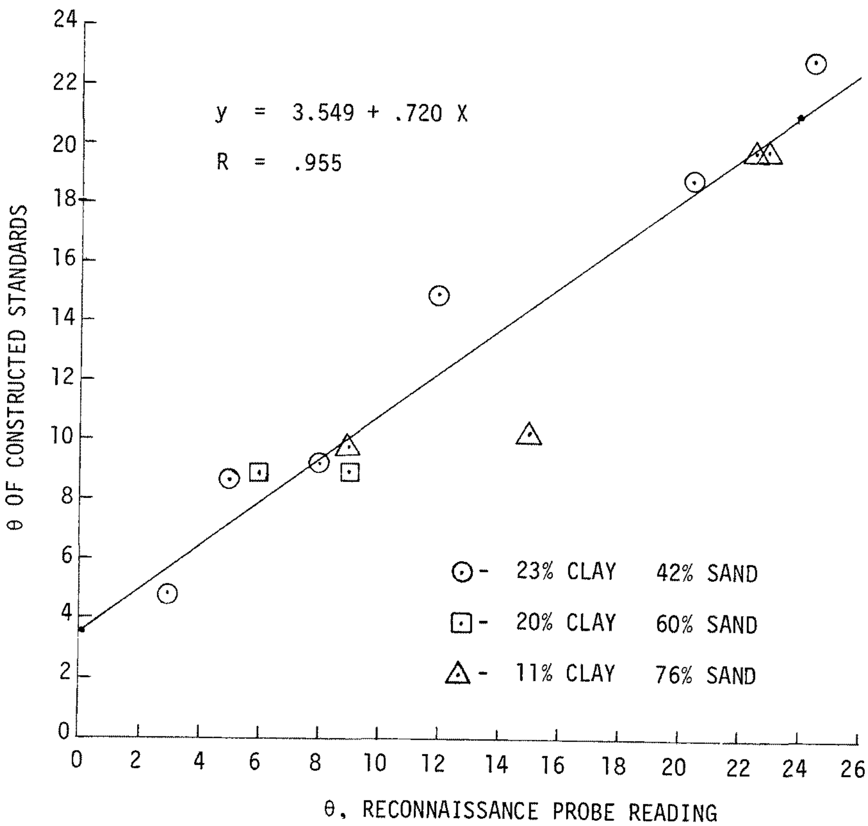


Figure 20. Relationship between θ and probe reading for the Reconnaissance probe on loan from the U. S. Environmental Protection Agency.

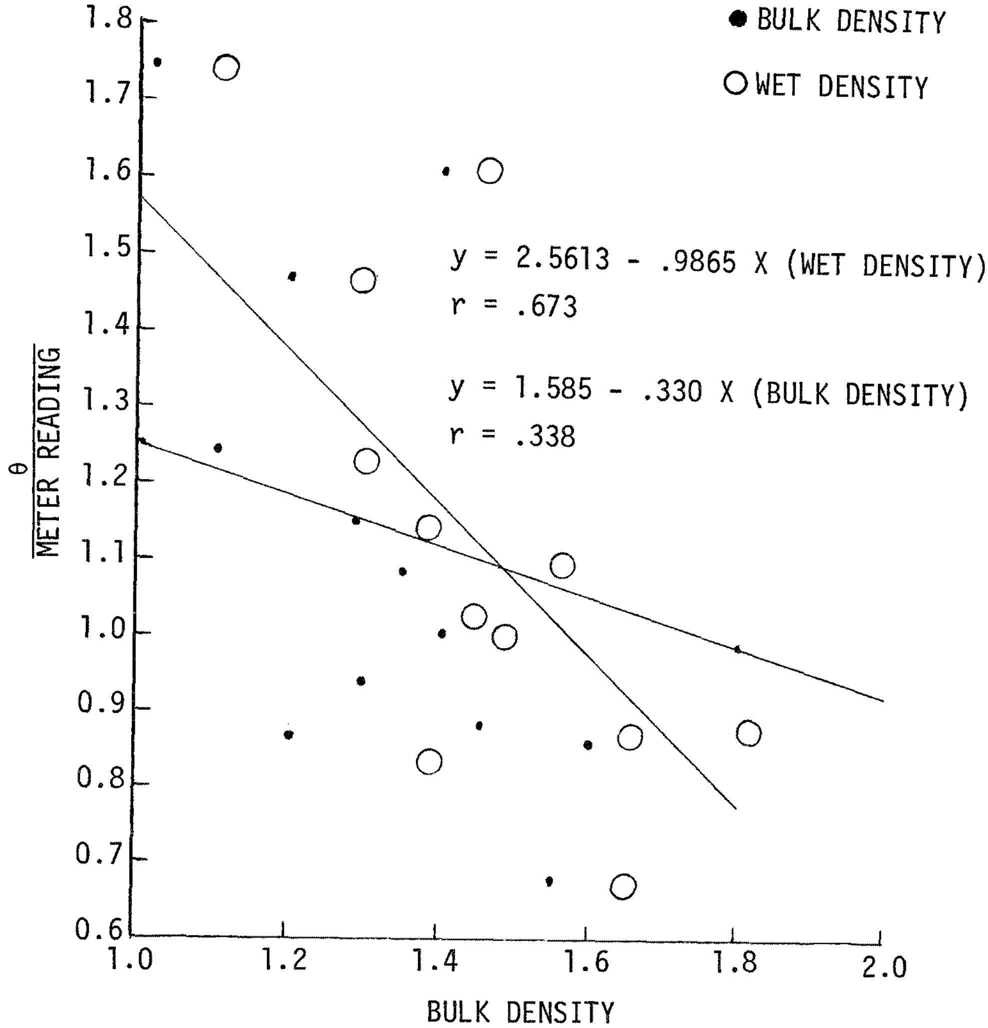


Figure 21. Relationship between θ/meter reading and density for the Reconnaissance probe.

standards. It can be readily seen that data correction using a calibration curve from the constructed standards shows a better distinction between zones with higher and lower soil-water contents, especially at the top and bottom of the profile. The surface 0.9 m is lower in bulk density and the differences between readings were not as great, and the moisture contents were relatively high compared to those in the middle of the profile. The water table beginning at 7.0 m was much more pronounced in that the values at 7.0 m and below were 3 to 6% higher than the layers immediately above. Where measurements from the profile were based on standards from the Company, it was not possible to distinguish where the water table began with the Well Reconnaissance probe and difficult with the Troxler probe in that the difference was only slightly over 2%. This difference was approximately 6% when the calibration curve from the constructed standards was used.

TABLE 9. COMPARISON OF MOISTURE CONTENT (PERCENT BY VOLUME) VALUES OBTAINED BY A TROXLER NEUTRON PROBE AND A WELL RECONNAISSANCE, INC., NEUTRON PROBE

Depth, m	Bulk density	Troxler		Well Reconnaissance	
		*	†	*	†
0.3	1.51	21.87	19.54	19.4	17.69
0.6	1.42	20.08	19.66	21.2	21.71
0.9	1.54	19.70	16.66	20.0	17.69
1.2	1.61	21.24	16.64	20.1	16.27
1.5	1.67	20.44	14.82	21.8	16.46
1.8	1.70	20.43	14.12	20.1	14.32
2.1	1.70	20.90	14.39	20.7	14.82
2.4	1.75	24.42	15.75	21.0	13.93
2.7	1.75	27.29	17.55	24.0	16.25
3.0	1.75	26.77	17.12	26.0	17.80
3.4	1.72	25.00	16.95	25.5	18.27
3.7	1.78	26.12	16.05	25.6	16.63
4.0	1.81	27.17	15.86	26.2	16.18
4.3	1.78	28.07	17.30	25.5	16.55
4.6	1.81	27.74	16.17	27.0	16.74
4.9	1.83	27.42	15.41	26.6	15.86
5.2	1.82	27.96	15.93	26.5	16.10
5.5	1.76	29.29	18.46	27.0	18.26
5.8	1.77	29.11	18.23	27.1	18.04
6.1	1.73	29.02	19.46	27.8	17.86
6.4	1.77	28.46	17.71	26.6	17.66
6.7	1.78	28.12	17.26	26.6	17.36
7.0	1.64	30.98	23.62	25.9	20.92
7.3	1.70	31.04	21.77	28.0	20.43
7.6	1.67	31.40	22.92	28.5	22.32
7.9	1.70	30.18	21.13	28.0	22.93
8.2	1.73	29.69	19.89	27.9	19.90

*Based on Company standards.
†Based on constructed standards and corrected for bulk density.

Comparison of Soil-Water Content Changes of Various Irrigation Systems During the Growing Season--

The small change in soil-water content (2 to 5% by volume) in a given season was typical of all soil profiles in all irrigation systems. Figure 22 shows the maximum and minimum soil-water content in profiles from the four irrigation systems. The small change in water content indicates the excellent possibility of water losses to irrigation return flow. The water content varied more in the automatically-irrigated system than in the other systems.

The clay content varied from 9 to 38% within the soil profile. As will be discussed later, the zones of high sand or low clay content created problems relative to obtaining soil-water extracts. In some cases, soil-water extracts were never obtained from zones which had high sand contents or low clay contents. This was probably due to a combination of low soil-water content and poor contact between the soil and the porous bulbs.

Soil-Water Content Changes Between Years--

Figure 23 shows the changes in soil-water content during the four years of the study in one of the sprinkler-irrigated plots. During the first growing season (May 11 to July 18, 1971), change in soil-water content was between 0 and 3.0 m. The water content increased over 5% by volume between 1.2 and 1.8 m. Between May 11, 1971 and April 12, 1972 there was a further increase in soil-water content in a portion of this zone (0.9 to 2.4 m) and a major increase to a depth of 7.6 m. This was due to the 32.9 cm of rain received during this period. The water table rose from 6.1 to 5.5 m.

During the 1972 crop year (April 12 to July 18, Figure 23), there was little change in soil-water content in the profile. However, between July 18, 1972 and May 8, 1973, there was another major increase in soil-water content between 4.6 and 6.1 m, indicating a further rise in water table due to rainfall (74 cm) received between the two dates. The fact that there was little change in water content above these two zones indicates that the zones were at "field capacity" and could not retain more water and that the increase was due to recharge in another area.

Except for minor changes in the surface, the major changes in water content during the 1973 growing season were between 4.6 and 6.1 m. The decreased water content indicated that the water table receded during this period. With the exception of the surface samples, there was little change between May 1973 and July 1974. The soil-water content on the first date of the study is included in this figure to delineate the overall changes during the course of the study. It can be seen that the water content increased from 2 to 8% between the surface and the bottom of the profile. This was true of all plots. Thus, the area has a fluctuating water table, and irrigation enhances the possibility that excess water from rainfall and irrigation and excess nitrates from fertilization will reach the water table by increasing the soil-water content of zones that might otherwise be dry under nonirrigated conditions.

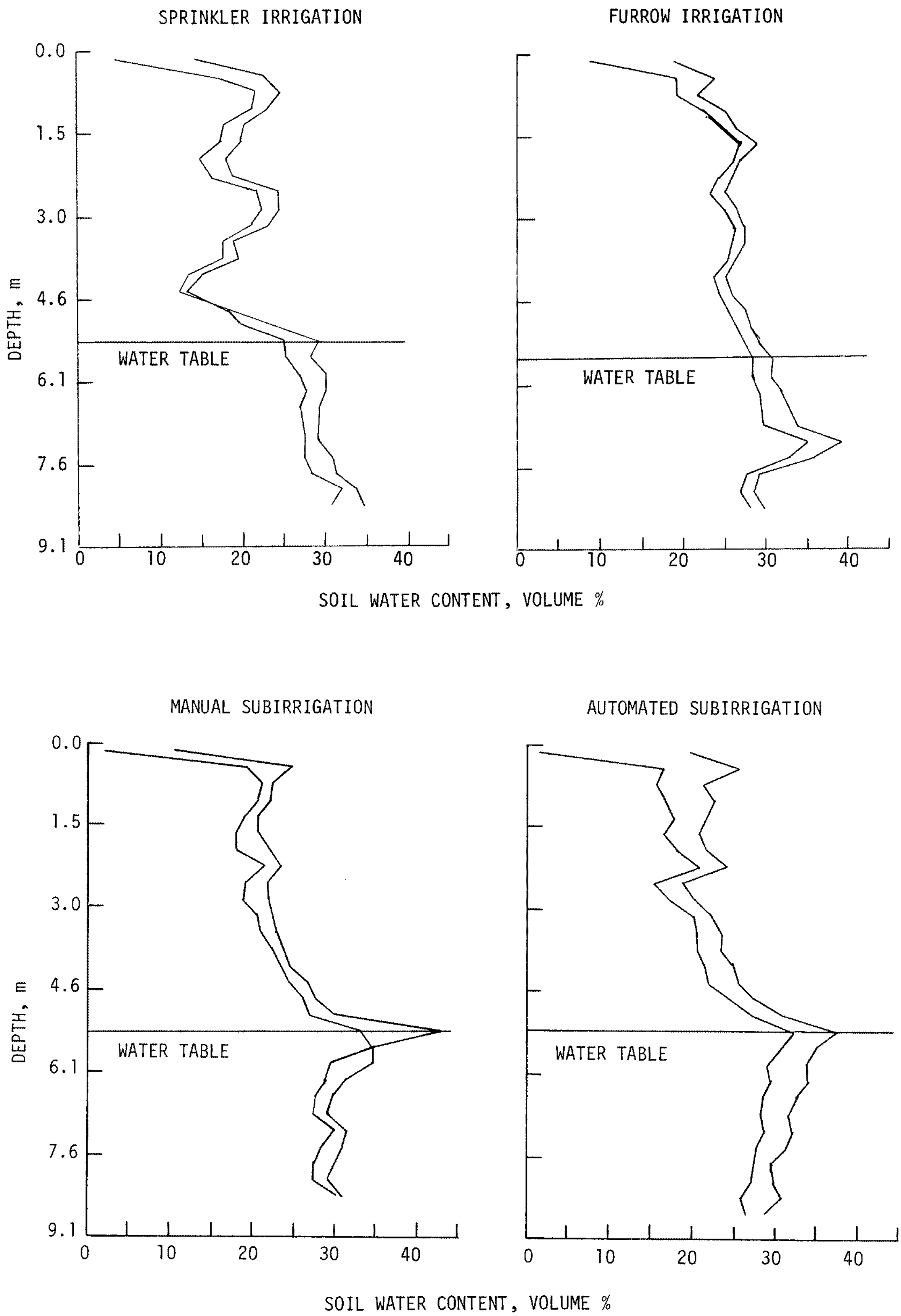


Figure 22. Maximum and minimum soil-water contents of profiles from the different irrigation systems during 1972.

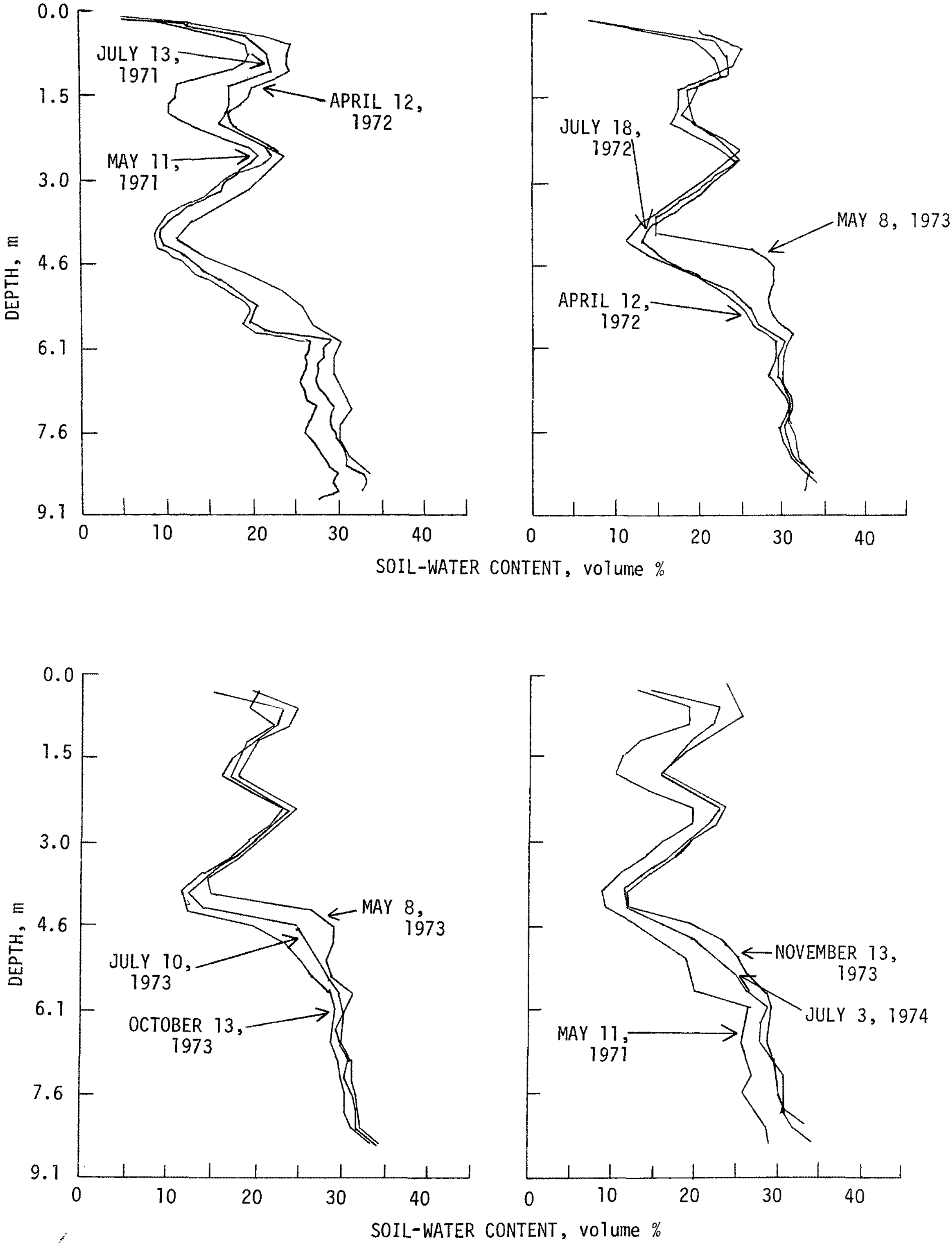


Figure 23. Changes in soil-water content in a sprinkler-irrigated plot during the course of the study.

Hydraulic Conductivity Studies

A separate study was initiated in 1973 using small plots to determine the hydraulic conductivity of the Miles loamy fine sand at the field site. The conductivities were determined in 30-cm increments of the soil profile between 15 and 290 cm according to the procedure of Hillel, et al. (9).

Tables 10 through 15 show the hydraulic conductivities (K) along with the moisture content (θ), matric suction (ψ), texture, and bulk densities. The profiles had a wide range of textures (clay content 8 to 37%) and bulk densities (1.39 to 1.67). The profiles were thus characterized by layers having major differences in texture and bulk density. As would be expected, the profiles exhibited considerable variability in soil-water characteristics. In Figure 24, the hydraulic conductivities for the different depths at one location are shown along with information on the soil texture and bulk density. It can be seen that four layers in the profile had 16 or 17% clay and 71 or 72% sand, yet the hydraulic conductivity curves show considerable difference in hydraulic conductivity at a particular soil-water content. In general, for a given soil texture, the highest water content for a particular conductivity occurred in zones immediately above a zone of higher clay content which was followed by zones of lower clay content. In this profile, this was true for the zones located at 76 cm and 229 cm. Although the clay content at 137, 167, and 198 cm was similar to that at 76 cm, and the content at 290 cm was similar to that at 229 cm, the zone above the zones which had high clay content (107-cm and 259-cm zones) had the highest moisture content for a particular hydraulic conductivity. The curves differ considerably in soil-water content for a particular hydraulic conductivity. They do, however, have some characteristics in common. The slope of all the curves is very similar indicating the rates of change in hydraulic conductivity for all depths are approximately the same. Further, 100-fold changes [0.254 to 25.4 millimeters per day (mm/da)] in hydraulic conductivity may occur with an increase in soil-water content of only 2 to 6% by volume. If an average of 4% by volume is assumed, in a 4.6-m profile (a depth at which the water table is often located) the addition of 184 mm of water to the profile would cause increases in hydraulic conductivity from less than 0.254 mm/da to over 25.4 mm/da. If the area had no crop, it is possible that water from excess rainfall or excess irrigation would reach the water table within one week.

Values for hydraulic conductivity were determined two to three times at each location. A comparison of the values obtained as a function of soil-water content and matric suction for the 76- and 229-cm depths are shown in Figures 25 and 26, respectively, for Plot 1. It can be seen that the conductivities at a particular soil-water content or matric suction vary considerably between the dates at which the tests were run. This may be due to differences in soil-water content of zones below the zones evaluated. It is visualized that such differences may have existed between the two dates, especially at Locations 1 and 2, because these were dryland plots prior to the initiation of these studies. Plot 3 was an irrigated plot and there was less change in hydraulic conductivity at a particular moisture content than with Plots 1 and 2.

TABLE 10. HYDRAULIC CONDUCTIVITY DATA AND VALUES OBTAINED FOR A MILES LOAMY FINE SAND, KNOX COUNTY, TEXAS, DURING SEPTEMBER 18 TO OCTOBER 3, 1973 AND OCTOBER 8 TO OCTOBER 29, 1973, AT LOCATION 1

			Experiment 1 September 18 to October 3, 1973				Experiment 2 October 8 to October 29, 1973			
Depth, cm	Particle size, %	Bulk density, g/cm^3	Time, da	Matric suction, cb	θ, cm^3/cm^3	K, mm/da	Time, da	Matric suction, cb	θ, cm^3/cm^3	K, mm/da
15	Sand 86	1.55	0.5	-1.5	.217	21.69	1.5	-1.5	.224	7.44
	Silt 6		1.0	-1.5	.206	8.84	3.0	0.1	.200	7.80
	Clay 8		4.0	1.2	.185	4.23				
			8.0	1.8	.168	2.87				
			12.0	2.0	.158	2.44				
46	Sand 82	1.52	0.5	-0.3	.253	71.51	1.5	-1.8	.254	13.10
	Silt 7		1.0	1.0	.244	18.72	3.0	0.0	.242	15.10
	Clay 11		4.0	2.6	.237	5.93				
			8.0	3.2	.234	3.95				
			12.0	3.5	.232	3.96				
76	Sand 74	1.53	0.5	-0.7	.246	17.43	1.5	-1.6	.246	11.76
	Silt 9		1.0	0.8	.242	4.09	3.0	0.2	.236	2.30
	Clay 17		4.0	2.2	.235	0.88	5.0	1.4	.232	0.24
			8.0	2.7	.232	0.51	10.0	2.1	.228	0.07
			12.0	3.0	.230	0.26	18.0	2.6	.226	0.04
107	Sand 71	1.56	0.5	0.0	.229	40.92	1.5	-0.4	.234	16.38
	Silt 10		1.0	1.8	.218	10.00	3.0	1.7	.211	3.87
	Clay 19		4.0	3.7	.204	1.34	5.0	3.2	.202	0.87
			8.0	4.4	.198	0.71	10.0	4.2	.194	0.20
			12.0	4.9	.195	0.42	18.0	5.2	.191	0.05
137	Sand 72	1.55	0.5	1.2	.232	25.23	1.5	1.1	.229	21.14
	Silt 11		1.0	2.9	.221	9.08	3.0	3.2	.209	5.24
	Clay 17		4.0	5.1	.202	1.87	5.0	4.6	.201	1.65
			8.0	6.1	.196	0.91	10.0	5.7	.192	0.59
			12.0	6.4	.191	0.57	18.0	6.6	.187	0.23
168	Sand 72	1.56	1.0	2.8	.219	61.89	1.5	1.6	.233	40.57
	Silt 11		4.0	4.6	.207	13.60	3.0	3.6	.212	10.10
	Clay 17		8.0	5.6	.199	11.18	5.0	4.5	.202	3.23
			12.0	6.2	.192	5.39	10.0	5.3	.192	1.02
							18.0	6.0	.186	0.37
198	Sand 71	1.60					1.5	0.4	.260	128.82
	Silt 13						3.0	2.3	.245	29.03
	Clay 16						5.0	3.2	.234	7.26
							10.0	4.2	.225	1.66
							18.0	5.2	.220	0.68
229	Sand 69	1.64					1.5	-1.4	.273	93.57
	Silt 11						3.0	0.6	.265	27.04
	Clay 20						5.0	2.1	.260	6.30
							10.0	3.9	.257	1.27
							18.0	5.0	.254	0.39
259	Sand 66	1.68					1.5	0.1	.259	19.64
	Silt 11						3.0	1.6	.246	6.85
	Clay 23						5.0	3.0	.241	2.89
							10.0	4.8	.237	0.94
							18.0	5.9	.234	0.39
290	Sand 67	1.72					3.0	3.0	.231	19.69
	Silt 12						5.0	4.0	.224	6.95
	Clay 21						10.0	5.2	.218	2.21
							18.0	6.2	.214	1.03

TABLE 11. HYDRAULIC CONDUCTIVITY DATA AND VALUES OBTAINED FOR A MILES LOAMY FINE SAND, KNOX COUNTY, TEXAS, DURING SEPTEMBER 21 TO OCTOBER 5, 1973, LOCATION 2

Depth, cm	Particle size, %	Bulk density, g/cm³	Time, da	Matric suction, cb	θ, cm³/cm³	K, mm/da
15	Sand 85	1.49	0.7	-1.5	.236	1.21
	Silt 6		1.5	-0.9	.228	0.48
	Clay 9		3.0	-0.1	.221	0.33
			6.0	1.0	.210	0.24
			10.0	2.0	.199	0.18
			15.0	2.5	.189	0.11
46	Sand 81	1.45	0.7	-1.3	.232	3.91
	Silt 8		1.5	-0.3	.225	1.35
	Clay 11		3.0	0.8	.219	0.75
			6.0	1.9	.214	0.38
			10.0	2.4	.211	0.24
			15.0	2.6	.209	0.14
76	Sand 74	1.42	0.7	0.5	.237	15.89
	Silt 12		1.5	1.4	.225	4.29
	Clay 14		3.0	2.6	.218	1.74
			6.0	3.7	.214	0.76
			10.0	4.3	.212	0.43
			15.0	4.6	.211	0.23
107	Sand 68	1.45	0.7	-0.3	.249	59.72
	Silt 15		1.5	1.1	.239	15.06
	Clay 17		3.0	2.5	.232	3.62
			6.0	3.8	.227	1.43
			10.0	4.4	.225	0.89
			15.0	4.8	.224	0.47
137	Sand 66	1.52	1.5	-0.4	.257	18.29
	Silt 15		3.0	1.0	.251	21.61
	Clay 19		6.0	2.1	.248	14.56
			10.0	2.7	.247	4.76
			15.0	3.1	.246	4.57
168	Sand 57	1.65	0.7	-2.0	.267	30.96
	Silt 18		1.5	-1.7	.270	15.24
	Clay 25		3.0	-1.5	.269	-
			6.0	-0.5	.270	8.76
			10.0	0.2	.268	5.88
			15.0	0.5	.268	5.25
198	Sand 50	1.74	0.7	-2.0	.266	27.38
	Silt 21		1.5	-2.3	.264	13.09
	Clay 29		3.0	-3.8	.264	6.65
			6.0	-2.4	.263	2.67
			10.0	-1.3	.263	1.19
			15.0	-0.8	.263	0.63
229	Sand 45	1.71	0.7	-2.1	.256	13.67
	Silt 24		1.5	-2.3	.258	7.47
	Clay 31		3.0	-3.1	.255	4.34
			6.0	-2.0	.254	1.02
			10.0	-0.8	.253	0.85
			15.0	-0.4	.253	0.60
259	Sand 44	1.62	0.7	-0.2	.243	19.69
	Silt 26		1.5	-1.9	.247	9.41
	Clay 30		3.0	-2.6	.243	9.16
			6.0	-1.3	.240	1.95
			10.0	0.0	.237	1.09
			15.0	0.4	.236	0.55
290	Sand 50	1.60	0.7	0.4	.239	6.02
	Silt 24		1.5	-1.8	.247	11.43
	Clay 26		3.0	-2.8	.248	7.63
			6.0	-1.5	.249	2.03
			10.0	0.0	.245	1.60
			15.0	0.4	.245	1.10

TABLE 12. HYDRAULIC CONDUCTIVITY DATA AND VALUES OBTAINED FOR A MILES LOAMY FINE SAND, KNOX COUNTY, TEXAS, DURING SEPTEMBER 21 TO OCTOBER 5, 1973, LOCATION 3

Depth, cm	Particle size, %	Bulk density, g/cm^3	Time, da	Matric suction, cb	θ, cm^3/cm^3	K, mm/da
15	Sand 82	1.49	0.6	-1.4	.228	34.54
	Silt 7		1.5	0.0	.220	13.01
	Clay 11		4.0	2.8	.209	18.06
			9.0	4.9	.196	30.48
			15.0	5.5	.187	18.62
46	Sand 80	1.39	0.6	-3.1	.245	188.98
	Silt 8		1.5	-1.1	.227	54.86
	Clay 12		4.0	1.8	.217	37.26
			9.0	3.0	.211	50.80
			15.0	3.4	.208	32.18
76	Sand 70	1.36	0.6	-2.3	.271	241.38
	Silt 13		1.5	-0.8	.249	39.24
	Clay 17		4.0	1.2	.240	11.15
			9.0	2.0	.234	4.62
			15.0	2.3	.232	2.79
107	Sand 62	1.52	0.6	-1.6	.275	613.21
	Silt 15		1.5	-0.9	.271	212.47
	Clay 23		4.0	-1.5	.267	0.00
			9.0	1.7	.265	0.00
			15.0	1.6	.263	134.62
137	Sand 57	1.67	0.6	-0.4	.285	-517.80
	Silt 15		1.5	-4.1	.284	-12.62
	Clay 28		4.0	-3.7	.285	-3.31
			9.0	-2.0	.285	-0.91
			15.0	0.9	.283	-4.95
168	Sand 43	1.73	0.6	-5.0	.277	29.13
	Silt 23		1.5	-5.8	.277	5.34
	Clay 34		4.0	-6.1	.277	1.20
			9.0	-5.1	.275	0.40
			15.0	-3.1	.278	-0.33
198	Sand 35	1.71	0.6	-2.5	.264	31.07
	Silt 28		1.5	-3.9	.264	7.39
	Clay 37		4.0	-3.7	.259	1.39
			9.0	-3.2	.260	0.42
			15.0	-2.3	.258	-0.34
229	Sand 37	1.63	0.6	-1.7	.264	101.21
	Silt 28		1.5	-3.1	.264	12.69
	Clay 35		4.0	-3.0	.259	3.43
			9.0	-1.8	.258	1.04
			15.0	1.0	.256	-0.56
259	Sand 43	1.56	0.6	-2.5	.265	50.63
	Silt 27		1.5	-2.8	.252	7.49
	Clay 30		4.0	-2.5	.246	2.32
			9.0	-1.2	.243	0.54
			15.0	-0.5	.240	-0.32
290	Sand 46	1.65	0.6	-1.7	.284	32.83
	Silt 25		1.5	-1.8	.272	13.11
	Clay 29		4.0	-1.8	.264	4.05
			9.0	-0.5	.262	1.12
			15.0	0.5	.259	0.32

TABLE 13. HYDRAULIC CONDUCTIVITY DATA AND VALUES OBTAINED FOR A MILES LOAMY FINE SAND, KNOX COUNTY, TEXAS, DURING AUGUST 7 TO SEPTEMBER 6, 1974, LOCATION 1

Depth, cm	Particle size, %	Bulk density, g/cm^3	Time, da	Matric suction, cb	θ, cm^3/cm^3	K, mm/da
15	Sand 86	1.55	0.3	3.6	.231	8.13
	Silt 6		0.8	4.7	.216	5.49
	Clay 8		2.0	5.7	.198	3.32
			5.0	7.3	.173	3.16
			10.0	9.6	.145	4.02
			15.0	11.6	.131	2.38
			20.0	13.3	.127	0.91
46	Sand 82	1.52	0.3	1.4	.254	15.44
	Silt 7		0.8	2.4	.248	9.88
	Clay 11		2.0	3.2	.242	5.27
			5.0	4.5	.236	4.62
			10.0	6.0	.230	5.85
			15.0	6.9	.225	4.94
			20.0	7.6	.222	2.38
76	Sand 74	1.53	0.3	1.5	.248	11.80
	Silt 9		0.8	2.4	.242	5.79
	Clay 17		2.0	3.7	.237	2.37
			5.0	4.6	.231	1.11
			10.0	6.1	.227	1.07
			15.0	6.9	.224	0.26
			20.0	7.5	.222	0.11
107	Sand 71	1.56	0.3	1.7	.236	30.76
	Silt 10		0.8	3.1	.224	12.07
	Clay 19		2.0	4.4	.212	4.69
			5.0	6.5	.203	1.57
			10.0	8.6	.196	0.84
			15.0	9.2	.192	0.44
			20.0	9.5	.188	0.29
137	Sand 72	1.55	0.3	1.9	.228	25.97
	Silt 11		0.8	3.9	.217	11.40
	Clay 17		2.0	5.5	.208	4.92
			5.0	7.7	.199	2.13
			10.0	10.0	.192	1.54
			15.0	10.6	.187	0.69
			20.0	10.7	.183	0.38
168	Sand 72	1.56	0.3	1.4	.247	142.75
	Silt 11		0.8	3.3	.232	75.40
	Clay 17		2.0	4.8	.219	54.76
			5.0	6.7	.206	23.68
			10.0	8.4	.197	4.22
			15.0	9.3	.191	2.37
			20.0	9.7	.186	8.60

continued

TABLE 13. (continued)

Depth, cm	Particle size, %	Bulk density, g/cm³	Time, da	Matric suction, cb	θ, cm³/cm³	K, mm/da
198	Sand 71	1.60	0.3	-1.4	.263	141.51
	Silt 13		0.8	0.0	.256	85.88
	Clay 16		2.0	1.4	.247	20.12
			5.0	3.1	.236	6.11
			10.0	4.9	.230	4.56
			15.0	6.2	.227	2.60
			20.0	7.0	.225	8.96
229	Sand 69	1.64	0.3	-3.2	.271	149.39
	Silt 11		0.8	-1.7	.268	91.06
	Clay 20		2.0	0.0	.264	6.92
			5.0	2.4	.260	6.52
			10.0	4.5	.257	4.85
			15.0	5.9	.254	2.77
			20.0	6.7	.252	0.56
259	Sand 66	1.68	0.3	-3.1	.260	55.65
	Silt 11		0.8	-1.1	.255	22.79
	Clay 23		2.0	1.2	.258	10.99
			5.0	4.6	.240	4.96
			10.0	6.2	.235	2.38
			15.0	7.5	.233	1.16
			20.0	8.0	.230	0.66
290	Sand 67	1.72	0.3	-2.0	.248	39.92
	Silt 12		0.8	-1.1	.240	25.22
	Clay 21		2.0	1.2	.231	11.47
			5.0	4.1	.222	4.76
			10.0	6.2	.216	2.13
			15.0	7.5	.213	1.31
			20.0	8.0	.210	0.74
320	Sand 69	1.73	0.3	-1.0	.248	43.95
	Silt 12		0.8	0.5	.239	27.73
	Clay 19		2.0	2.2	.232	12.50
			5.0	4.8	.224	5.23
			10.0	7.6	.218	2.24
			15.0	9.1	.216	1.33
			20.0	9.7	.214	0.77

TABLE 14. HYDRAULIC CONDUCTIVITY DATA AND VALUES OBTAINED FOR A MILES LOAMY FINE SAND, KNOX COUNTY, TEXAS, DURING AUGUST 7 TO SEPTEMBER 6, 1974, LOCATION 2

Depth, cm	Particle size, %	Bulk density, g/cm^3	Time, da	Matric suction, cb	θ, cm^3/cm^3	K, mm/da
15	Sand 85	1.49	0.3	2.3	.243	1.22
	Silt 6		0.8	3.3	.237	0.74
	Clay 9		2.0	4.3	.227	0.63
			5.0	6.2	.205	0.72
			10.0	9.0	.175	1.10
			15.0	11.4	.151	1.16
			20.0	13.4	.137	1.28
46	Sand 81	1.45	0.3	1.3	.233	3.52
	Silt 8		0.8	2.5	.227	1.79
	Clay 11		2.0	3.5	.227	1.14
			5.0	5.1	.216	1.09
			10.0	6.3	.209	1.50
			15.0	6.6	.205	1.52
			20.0	6.8	.202	1.89
76	Sand 74	1.42	0.3	2.3	.238	32.92
	Silt 12		0.8	3.3	.231	16.79
	Clay 14		2.0	4.2	.223	6.86
			5.0	5.4	.216	2.62
			10.0	6.3	.212	1.71
			15.0	6.6	.210	1.52
			20.0	6.8	.209	1.07
107	Sand 68	1.45	0.3	0.6	.256	55.83
	Silt 15		0.8	1.4	.249	39.56
	Clay 17		2.0	2.3	.241	29.35
			5.0	3.7	.233	29.83
			10.0	4.8	.229	2.80
			15.0	5.2	.227	1.83
			20.0	5.4	.226	0.85
137	Sand 66	1.52	0.3	-1.1	.263	36.84
	Silt 15		0.8	0.1	.260	13.77
	Clay 19		2.0	0.7	.256	6.78
			5.0	1.7	.251	4.68
			10.0	2.7	.249	4.34
			15.0	3.2	.248	5.64
			20.0	3.6	.248	3.57
168	Sand 57	1.65	0.3	-0.6	.268	18.87
	Silt 18		0.8	0.0	.268	13.21
	Clay 25		2.0	0.0	.268	13.67
			5.0	0.8	.268	4.55
			10.0	1.4	.269	2.16
			15.0	1.6	.269	1.42
			20.0	1.8	.268	1.25

continued

TABLE 14. (continued)

Depth, cm	Particle size, %	Bulk density, g/cm³	Time, da	Matric suction, cb	θ, cm³/cm³	K, mm/da
198	Sand 50	1.74	0.3	-0.8	.261	1379.22
	Silt 21		0.8	-0.9	.261	264.03
	Clay 29		2.0	-1.2	.261	14.86
			5.0	-0.2	.261	9.25
			10.0	0.7	.261	3.53
			15.0	0.9	.261	1.88
			20.0	1.0	.261	1.30
229	Sand 45	1.71	0.3	-3.7	.256	75.82
	Silt 24		0.8	-3.6	.256	21.13
	Clay 31		2.0	-3.3	.255	12.27
			5.0	-2.2	.255	4.75
			10.0	-1.0	.255	2.85
			15.0	-0.4	.255	1.80
			20.0	-0.2	.253	1.45
259	Sand 44	1.62	0.3	-3.1	.252	13.11
	Silt 26		0.8	-2.6	.248	4.72
	Clay 30		2.0	-2.0	.242	2.06
			5.0	-1.1	.237	1.12
			10.0	-0.1	.234	0.69
			15.0	0.6	.234	0.48
			20.0	0.8	.234	0.40
290	Sand 50	1.60	0.3	-1.8	.259	149.96
	Silt 24		0.8	-1.3	.255	176.17
	Clay 26		2.0	-0.7	.252	43.97
			5.0	0.3	.249	13.82
			10.0	1.3	.247	3.51
			15.0	1.8	.247	2.85
			20.0	1.9	.246	2.31
320	Sand 52	1.64	0.3	-2.9	.288	158.50
	Silt 22		0.8	-2.6	.285	193.37
	Clay 26		2.0	-1.9	.281	48.54
			5.0	-0.7	.277	16.51
			10.0	0.4	.275	3.75
			15.0	1.8	.275	3.00
			20.0	1.0	.275	2.39

TABLE 15. HYDRAULIC CONDUCTIVITY DATA AND VALUES OBTAINED FOR A MILES LOAMY FINE SAND, KNOX COUNTY, TEXAS, DURING AUGUST 7 TO SEPTEMBER 6, 1974, LOCATION 3

Depth, cm	Particle size, %	Bulk density, g/cm^3	Time, da	Matric suction, cb	θ, cm^3/cm^3	K, mm/da
15	Sand 82	1.49	0.3	3.2	.238	1.13
	Silt 7		0.8	4.8	.234	0.65
	Clay 11		2.0	5.9	.226	0.56
			5.0	6.2	.211	0.46
			10.0	8.7	.191	0.47
			15.0	9.9	.174	0.59
			20.0	10.8	.162	0.55
46	Sand 80	1.39	0.3	1.1	.253	6.39
	Silt 8		0.8	2.8	.243	2.91
	Clay 12		2.0	3.9	.233	1.47
			5.0	5.1	.224	0.86
			10.0	6.1	.217	0.76
			15.0	6.8	.212	0.96
			20.0	7.4	.213	0.91
76	Sand 70	1.36	0.3	1.5	.271	35.05
	Silt 13		0.8	2.7	.263	53.03
	Clay 17		2.0	3.7	.254	14.20
			5.0	4.1	.249	9.23
			10.0	5.1	.246	5.94
			15.0	5.3	.244	3.23
			20.0	5.4	.243	3.29
107	Sand 62	1.52	0.3	-0.1	.272	69.12
	Silt 15		0.8	1.1	.270	18.90
	Clay 23		2.0	1.7	.269	513.08
			5.0	2.7	.271	12.31
			10.0	3.0	.270	-1.75
			15.0	3.1	.270	-8.69
			20.0	3.2	.269	-6.10
137	Sand 57	1.67	0.3	-1.5	.279	23.52
	Silt 15		0.8	0.1	.279	14.12
	Clay 28		2.0	-0.1	.280	43.69
			5.0	0.7	.278	5.15
			10.0	-0.9	.280	2.67
			15.0	0.7	.281	7.81
			20.0	1.1	.283	1.34
168	Sand 43	1.73	0.3	-1.9	.274	14.10
	Silt 23		0.8	-1.1	.272	10.67
	Clay 34		2.0	-1.4	.272	6.50
			5.0	-0.7	.273	2.75
			10.0	-2.6	.273	0.67
			15.0	-1.0	.274	0.54
			20.0	-0.4	.273	0.00

continued

TABLE 15. (continued)

Depth cm	Particle size, %	Bulk density, g/cm³	Time, da	Matric suction, cb	θ cm³/cm³	K, mm/da
198	Sand 35	1.71	0.3	-0.6	.266	17.84
	Silt 28		0.8	-1.3	.266	7.77
	Clay 37		2.0	-1.3	.266	6.87
			5.0	-0.4	.267	1.86
			10.0	-0.7	.268	0.53
			15.0	-0.4	.266	0.52
			20.0	-0.4	.266	0.00
229	Sand 37	1.63	0.3	-0.1	.259	30.87
	Silt 28		0.8	-0.5	.257	9.61
	Clay 35		2.0	-0.1	.255	9.13
			5.0	0.7	.252	2.28
			10.0	0.8	.252	0.66
			15.0	1.1	.252	0.59
			20.0	1.1	.252	0.53
259	Sand 43	1.56	0.3	-1.3	.258	39.96
	Silt 27		0.8	-0.7	.253	18.15
	Clay 30		2.0	-0.1	.249	18.53
			5.0	0.7	.245	6.25
			10.0	1.4	.242	1.51
			15.0	2.0	.240	1.33
			20.0	2.3	.239	0.93
290	Sand 46	1.65	0.3	-1.1	.276	23.90
	Silt 25		0.8	-0.7	.272	11.34
	Clay 29		2.0	-0.3	.269	9.21
			5.0	0.5	.265	2.71
			10.0	1.4	.263	0.94
			15.0	2.0	.262	0.75
			20.0	2.4	.262	0.70
320	Sand 44	1.75	0.3	-0.4	.279	29.32
	Silt 26		0.8	-0.2	.278	13.88
	Clay 30		2.0	0.2	.277	10.46
			5.0	1.0	.275	3.21
			10.0	1.8	.273	1.12
			15.0	2.4	.272	0.89
			20.0	2.8	.270	0.82

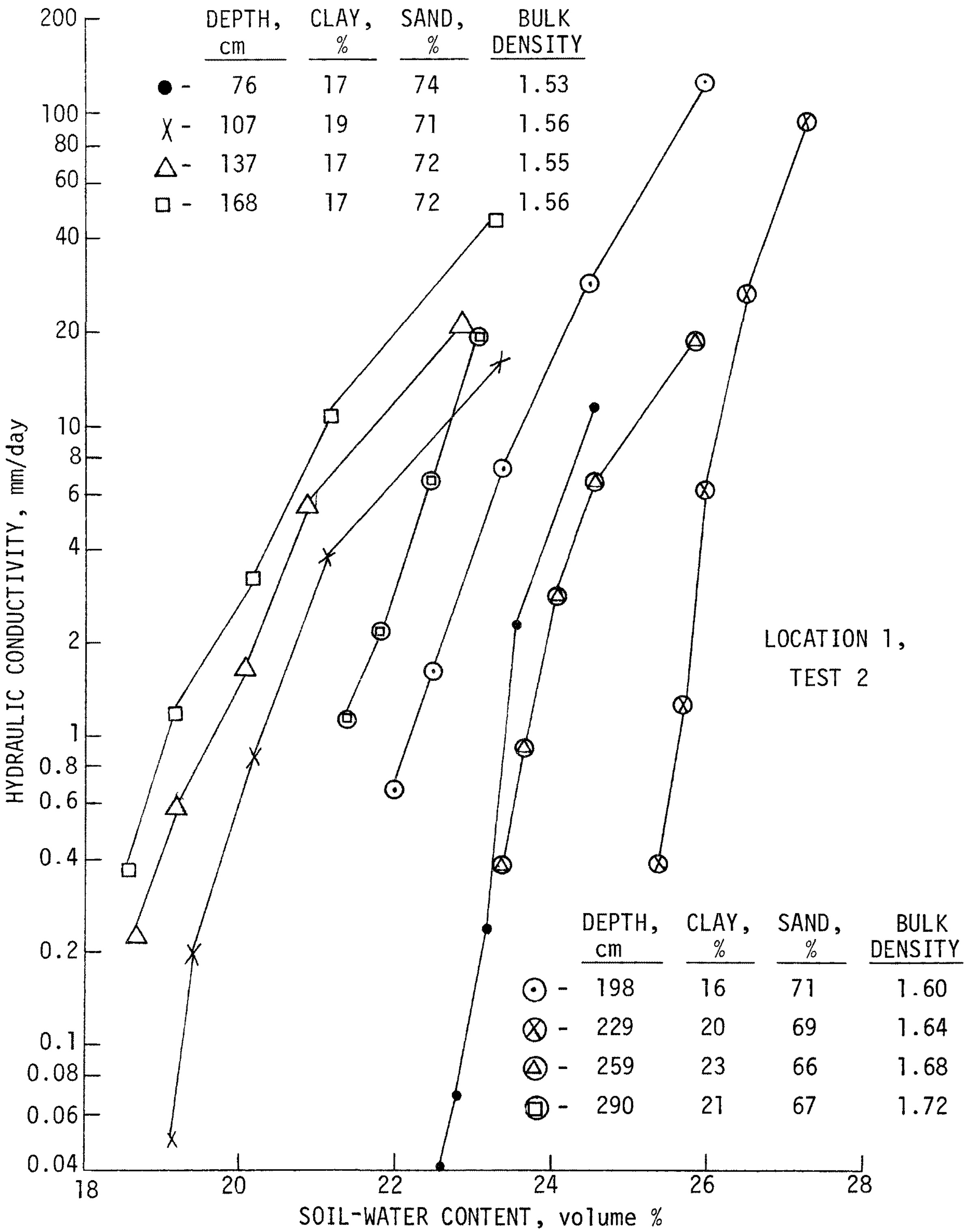


Figure 24. Hydraulic conductivity vs soil-water content for various depths in a Miles loamy fine sand in Knox County, Texas, 1973.

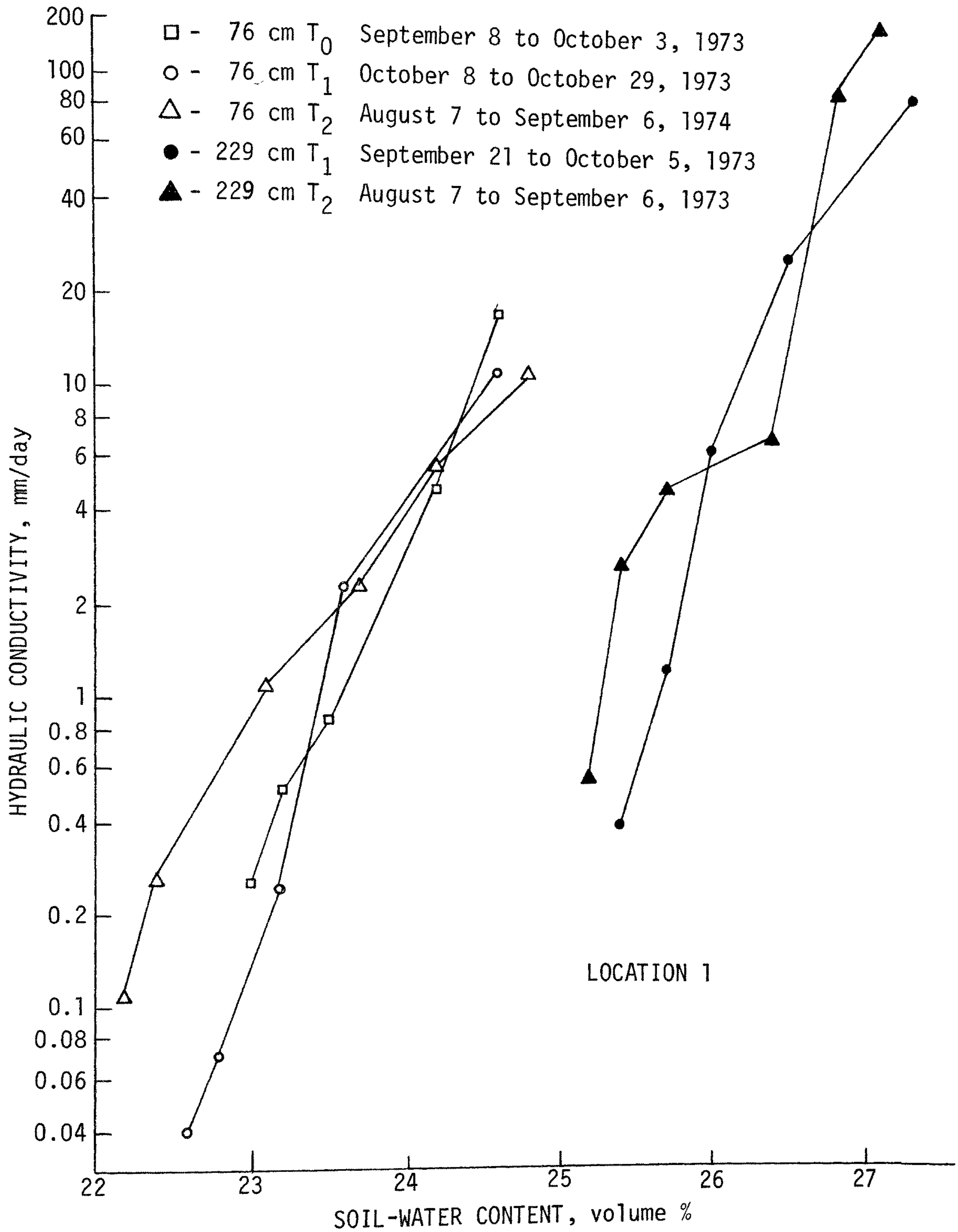


Figure 25. Hydraulic conductivity vs soil-water content at different times for the 76- and 229-cm depths in a Miles loamy fine sand.

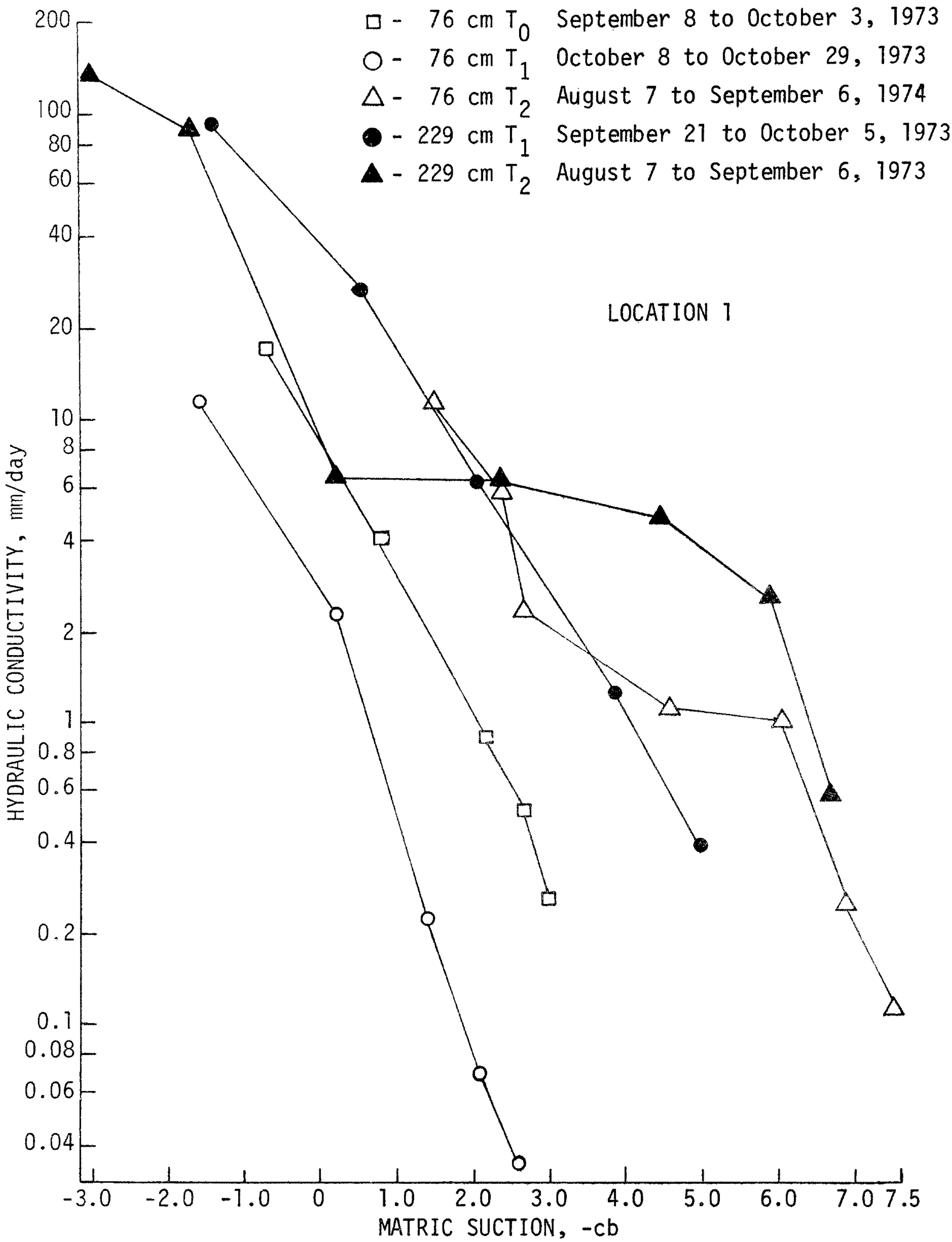


Figure 26. Hydraulic conductivity vs matric suction at different times for the 76- and 229-cm depths in a Miles loamy fine sand.

Another problem encountered in determining hydraulic conductivity was relative to the uneven pressure gradients. In Figure 27, negative hydraulic gradients were nonexistent at some measurement dates (0.6, 1.5, 4 and 9 days) for some depths (101.6 to 152.4 cm). The lack of gradients at these depths indicates that water moved through succeeding layers of the soil profile due to a pressure head rather than a pressure gradient. Overall, the pressure gradient was approximately 1 or greater after 15 days at 304.8 cm even with the existence of the pressure head at 101.6 to 152.4 cm.

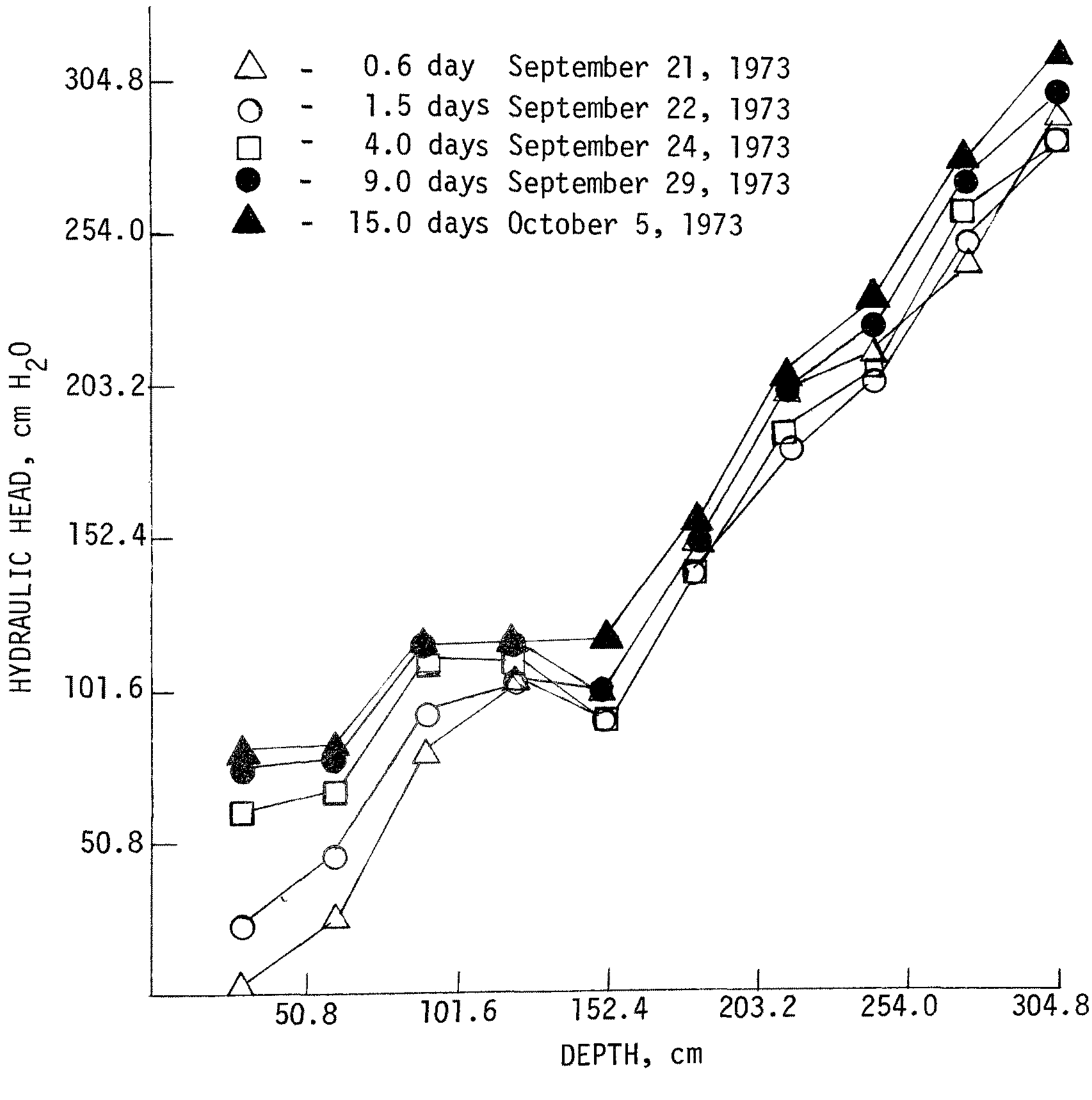


Figure 27. Hydraulic head at different depths on various dates in Plot 3 in Miles loamy fine sand soil.

It was not an objective of this project to develop a classical model for this soil type. With the problems described previously, it can be seen that such an undertaking would be a major project by itself. However, it was decided to develop a statistical model to evaluate hydraulic conductivity as a function of easily measurable variables using a stepwise regression analysis. The following soil characteristics were considered and measurements were made for 124 sets of data cases:

1. Location (Plot 1, 2 or 3).
2. Experiment number (1 or 2).
3. Observed hydraulic conductivity [centimeters per day (cm/da)].
4. θ - soil-water content (volume fraction) of layer of soil in question.
5. Upper θ - soil-water content of the layer of soil 30 cm above the layer of soil in question.
6. Lower θ - soil-water content of the layer of soil 30 cm below the layer of soil in question.
7. Field capacity - θ of soil after 12 to 18 days.
8. Upper field capacity - field capacity of the layer of soil 30 cm above the layer of soil in question.
9. Lower field capacity - field capacity of the layer of soil 30 cm below the layer of soil in question.
10. Bulk Density - ratio of weight of volume of soil to weight of equal volume of water.
11. Matric Suction - soil-water potential (cb).
12. Time - time at which all measurements were made after application of water to soil.
13. Depth - depth (cm) of soil at which all measurements were made.
14. Percent Sand.
15. Percent Silt.
16. Percent Clay.
17. Upper Sand - percent sand of the layer of soil 30 cm above the layer of soil in question.
18. Upper Silt - percent silt of the layer of soil 30 cm above the layer of soil in question.
19. Upper Clay - percent clay of the layer of soil 30 cm above the layer of soil in question.
20. Lower Sand - percent sand of the layer of soil 30 cm below the layer of soil in question.
21. Lower Silt - percent silt of the layer of soil 30 cm below the layer of soil in question.
22. Lower Clay - percent clay of the layer of soil 30 cm below the layer of soil in question.

From the original list of variables, field capacities, matric suction, and time were deleted because it was decided that these variables were difficult to measure or use. Then, many combinations of the remaining variables were introduced into the program. Numerous possible ratios, crossproducts, natural logs, square roots, squares, and cubes were used (some 250 combinations in all). From these combinations, the program selected those terms which best explained the variation in the dependent variable, natural log of the hydraulic conductivity. The model evolved is as follows:

$$\text{Natural Log of Hydraulic Conductivity (K)} = \qquad [8]$$

$$-.00372 \times \text{Lower Sand} \times \text{Lower } \theta - 4.99338 \times \text{Natural Log of Clay}$$

$$-34.50021 \times \frac{\text{Lower Silt}}{\text{Depth}} + 130.24553 \times \frac{\theta}{\text{Upper Sand}}$$

$$-77.32561 \times \frac{\text{Lower Clay}}{\text{Upper Sand}} - 27.00883 \times \frac{\theta}{\text{Lower Clay}}$$

$$+12.11346 \times \frac{\text{Lower Clay}}{\text{Upper } \theta} + 4.55044 \times \frac{\theta}{\text{Depth}}$$

$$-38.45392 \times \frac{\text{Lower Clay}}{\text{Lower } \theta} - .47643 \times \text{Upper Silt}$$

$$-29.06143 \times \frac{\text{Lower } \theta}{\text{Upper } \theta} + 8.75828 \times \frac{\text{Lower } \theta}{\text{Depth}}$$

$$-15.60952 \times \frac{\text{Upper } \theta}{\text{Lower } \theta} + 104.16374 \text{ (constant)}$$

$R^2 = .8368$ $\qquad R = .9148$

Natural log of standard error of estimate = 1.7214

Standard error of estimate = 5.5921 cm/da

Natural log of mean hydraulic conductivity = -1.5683

Mean hydraulic conductivity = 0.2084 cm/da

It should be understood that this model is a statistical model only and in no way describes the relationship between the variables.

Climate (Including Rainfall)

The method by Jensen, et al. (10) was used to calculate potential ET. Since the model involves maximum and minimum temperatures and relative humidities, wind run, and solar radiation, the ET potential obtained is an expression of all the parameters measured. Figure 28 shows the cumulative ET potentials obtained for the growing season of the first crop grown during each of the four years of the study along with the rainfall received during each of the growing seasons. It can be seen that the ET potential varied from 483.3 to 596.2 mm for a difference of 112.9 mm and that the rainfall during the growing season varied from 104.3 to 224.7 mm for a difference of 120.4 mm. Thus, the ET potential and rainfall for a given cropping season each varied over 100 mm. Sweet corn is one of the shorter season crops

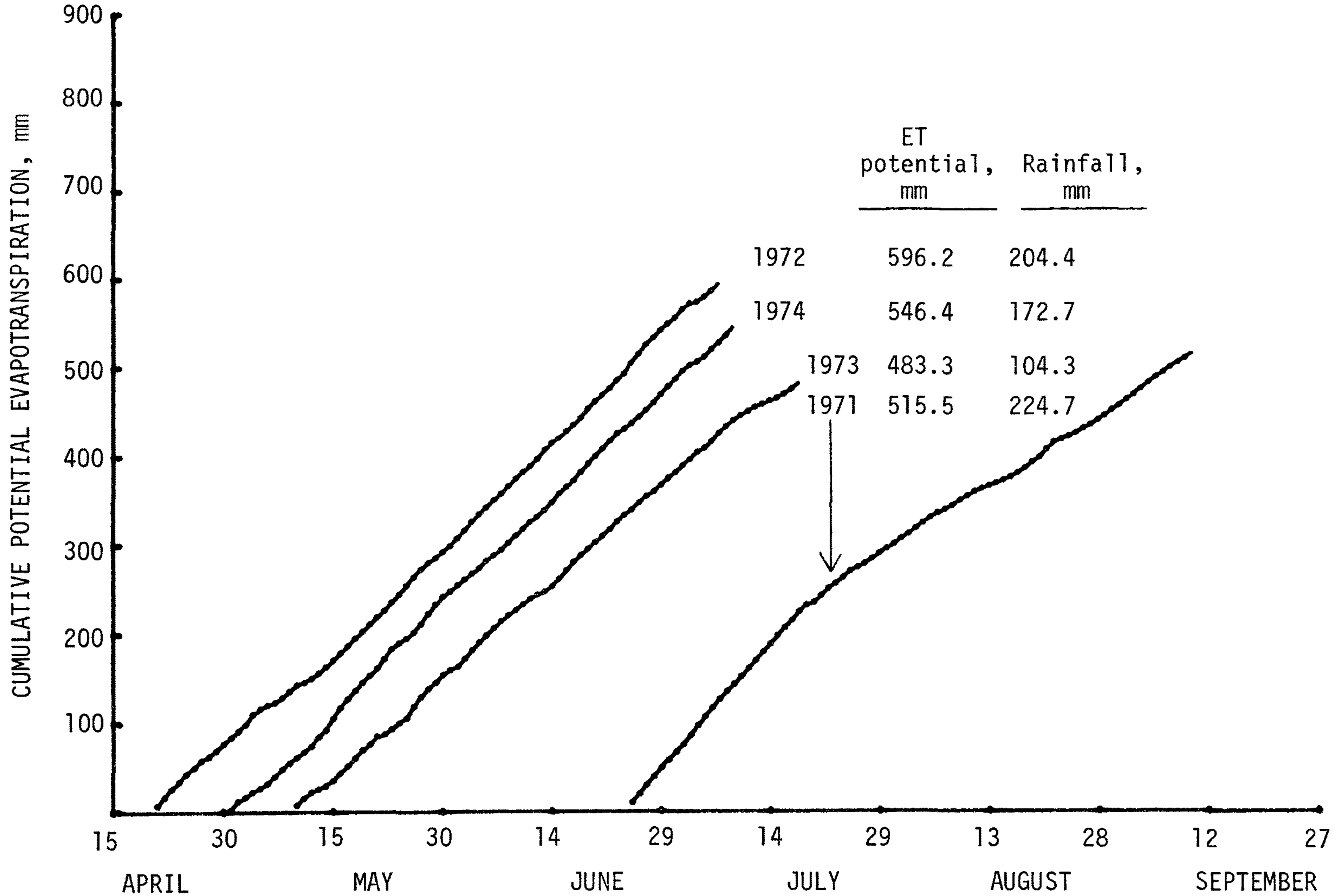


Figure 28. Cumulative ET potential following emergence of the first corn crop planted 1971-1974.

grown in the area, and larger variations could be expected for crops such as cotton, wheat, and grain sorghum which have considerably longer growing seasons.

This variation emphasizes the fallacy of irrigating crops on stage of growth. To minimize irrigation return flows from cropping systems in the area, it will be necessary to have a budgeting system involving the evaporative demand of the atmosphere, rainfall, crop water requirement, and water-holding capacity of the soil.

As the evaporative demand of the atmosphere and the rainfall have been discussed in this section, this leaves only the water demand of the crop. Ritchie (21) has pointed out that the water requirement of cotton and grain sorghum is related to the leaf area until the crop reaches a LAI of approximately 2.7. To determine if his finding is also true for the sweet corn used in the study, it was necessary to find a simplified method of determining LAI for the crop. Relationships between leaf area and stem diameter were derived as follows:

$$\text{Log } y = -1.169 + 2.389 \text{ Log } x \qquad r = .954 \qquad [9]$$

$$\sqrt{y} = -22.872 + 7.337 \sqrt{x} \qquad r = .952 \qquad [10]$$

where y = leaf area,
x = stem diameter 2.54 cm above the ground.

By multiplying the area of each individual plant times the plants per unit area and dividing by the area involved, it was possible to determine the LAI.

Another factor with respect to rainfall that should be mentioned is the amount of rainfall received during the year while a crop was not growing. Table 16 shows the rainfall by months, the total received, and the amount received with and without a crop during the years of the study. It can be seen that 417.9 to 518.7 mm rain was received while the area was without a crop. This amount is two to four times that received during the growing season and emphasizes the need to develop management practices to either exhaust all the potential pollutants such as nitrates through precision fertilization practices or grow crops for longer periods during the year to absorb any nitrates that might be available to be leached due to additions of excess rainfall or irrigation water.

Sampling

Soil-Water Extraction System--

Problems existed throughout the study with the soil-water extraction system. During the first year of the study, the 0.64-cm O.D. vacuum line had to be replaced with 1.27-cm O.D. line in order to obtain adequate vacuum for the soil-water extraction tubes. Even after the vacuum line was replaced, it was not possible to obtain samples from all extraction tubes.

TABLE 16. MONTHLY RAINFALL RECEIVED AT THE FIRST FIELD SITE, KNOX COUNTY, TEXAS, 1971-1974

	1971	1972	1973	1974
	mm			
January		3.8	57.2	8.6
February		10.2	43.4	6.4
March		2.5	82.0	25.4
April		11.4	56.9	56.4
May	152.4	94.2	19.6	34.3
June	14.0	69.1	52.6	80.3
July	70.1	71.9	69.1	4.3
August	153.2	126.5	17.8	35.6
September	74.9	106.7	166.9	170.2
October	201.4	208.8	33.0	143.5
November	15.2	18.0	20.1	10.2
December	41.9	-	-	35.6
Total	723.1	723.1	618.5	610.6
With crop	224.7	204.4	104.3	192.7
Without crop	498.4	518.7	514.2	417.9

As the season progressed, the number of soil-water samples extracted from the profile increased. This was probably due to better contact between the soil and soil-water extraction tubes and the soil-water content increasing at the lower depths to a point that adequate water was available for extraction. A high level of soil-water content was required in order to obtain samples of adequate size due to the high sand content of the soil. Most soil-water movement apparently ceased within a short period of time after water applications due to the high sand content of the soil. It was determined that the best procedure for obtaining samples was to begin extraction 24 hours following water additions and extract for a 48-hour period. The percentage of tubes from which extracts could be taken increased each year of the study. One of the problems in extracting the soil-water samples was the evaporation of the samples after they entered the extraction bottles. It was necessary to put mineral oil in each of the bottles to prevent the sample from evaporating. With this change, the concentrations of the ions in the water obtained from the water table and that from the irrigation wells were approximately the same. Any deviation of a large amount would have been noted between these two samples in that they came from the same source.

After the second year of the study, the vacuum was concentrated on the location in the plots with the deep extraction tubes. Some problems existed with the system following the second year of the study. The underground vacuum line had a considerable number of leaks. These occurred at insert tees that had cracked and insert male adapters that split due to weather exposure. Many shallow soil-water sampling tubes were broken from cultivation practices after the 1972 crop was harvested. The small nylon lines that connect the extraction tubes to the vacuum manifold had to be repaired or replaced. Weather exposure caused these lines to become brittle and break. During initial soil-water sampling, several deep extraction tubes were found to be broken and required replacement.

After the third year of the study, it was decided that adequate soil-water extract data had been obtained and that more effort should be expended on soil samples. The number of soil-water samples obtained was therefore decreased.

The dates on which samples were taken during the different years are shown in Table 17. Appropriate data from the different dates will be discussed under the results and discussion.

Comparison of Vacuum and Core Samples During 1971--

Due to the large number of soil-water extracts missing during the first year and the question of soil-water extracts vs core samples, it was decided to compare these two sampling methods. Comparisons were made between 1:1 extracts of core samples obtained at the beginning and end of the growing season and porous bulb soil-water extracts obtained at the end of the growing season. All samples were analyzed for nitrate-nitrogen (nitrate-N), chloride, sulfate, magnesium, ammonium, potassium, calcium, sodium, and conductivity. Concentrations of nitrate-N were similar to a depth of 210 cm for both sampling methods, but increased dramatically for vacuum samples below this depth (Figure 29). Chloride concentrations were similar for both systems down to 90 cm when vacuum sample concentrations again became much greater than 1:1 soil-water extracts. The other anion measured, sulfate, behaved differently in that concentration divergencies between sampling systems occurred in the upper levels of the profile (0 to 180 cm) and similar concentrations were measured at lower depths.

Concentrations of the divalent cations calcium and magnesium were similar for the two sampling systems in the upper portions of the profile (Figures 30 and 31). Conversely, for the monovalent cations potassium and sodium, concentrations were different in the upper portions of the profile and similar at lower depths. Ammonium concentrations were generally low (<4 ppm) and too erratic for comparisons. As might be expected, conductivity was dissimilar for the two sampling systems throughout the profile.

A correction was made to place the 1:1 extract data on a field moisture basis as follows:

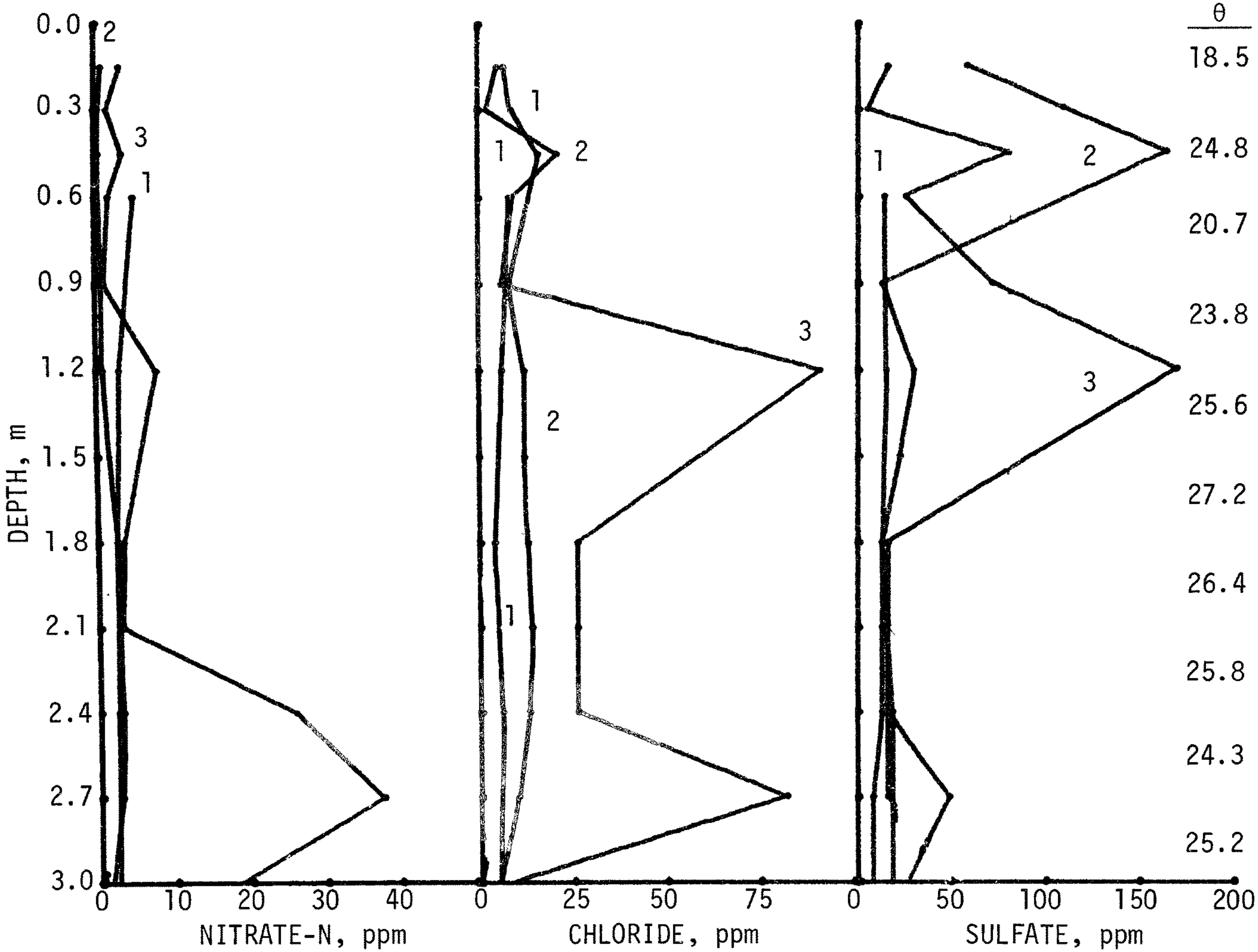
$$\frac{\text{1:1 extract concentration}}{\text{\% moisture of sample}} \times 100 = \text{field concentration} \qquad [11]$$

However, in Figure 32, where the correction for variable water content was made, this correction did not eliminate the differences between sampling systems.

TABLE 17. DATES ON WHICH SOIL-WATER EXTRACTS WERE OBTAINED FROM THE VARIOUS PLOTS IN KNOX COUNTY, TEXAS, 1971-1974

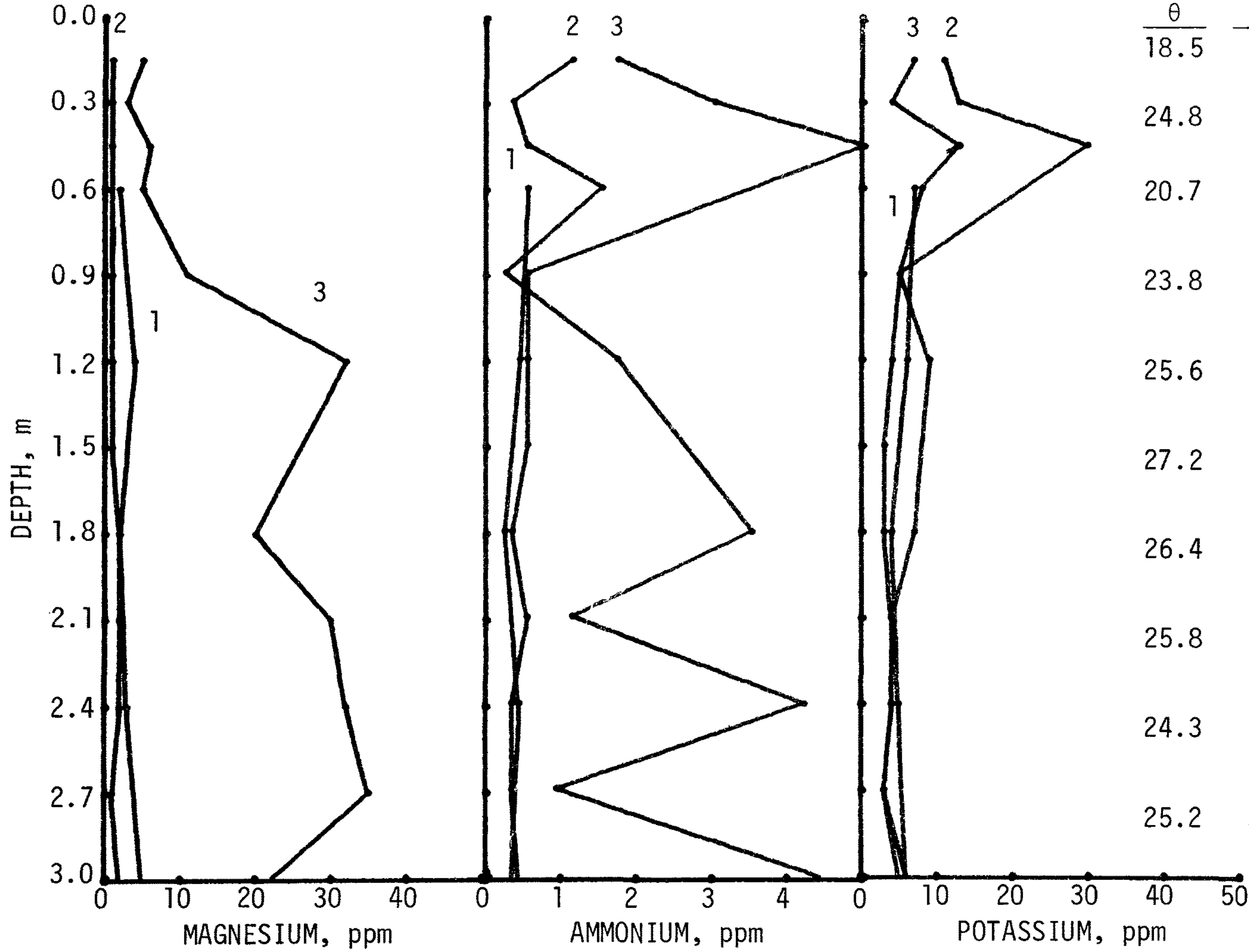
Date	Plot Numbers
	1971 - 1st crop
June 3	1-39
June 25	1-39
July 8	1-39
Aug. 2	1-39
Aug. 17	1-39
Sept. 3	1-39
	1971 - 2nd crop
Sept. 27	27, 38, 32, 33
	1972 - 1st crop
April 14	14-26
April 19	40, 41
April 20	42, 43
April 24	37-39, 44, 45
May 4	1-13
May 5	27-39
May 8	14-26, 40-45
May 30	45
May 31	15, 19, 41
June 1	16-18, 20, 36-39
June 2	42
June 5	1-14, 27, 29, 31-35
June 6	30, 40, 43, 44
June 8	22-26, 36
June 10	4, 9, 14-18, 20
June 12	27, 28, 30, 31, 33, 35, 38, 39
June 13	5, 21, 36, 42
June 22	5-7, 10, 17-19, 21, 22-26, 31-33, 36, 40-45
June 27	8, 11-13
June 28	2, 15, 17, 21, 23-26
June 30	5-7, 31, 36, 40, 41
July 3	34, 44, 45
July 5	5-7, 10, 17-19, 21, 31-33, 36, 40-45
	1972 - 2nd crop
July 28	6-8, 17-19, 33, 34
July 29	32
July 30	40-45
Aug. 14	6-8, 17-19, 32-34, 40-45
Aug. 28	6-8, 17-19, 32-34, 40-45
Aug. 31	19
Sept. 6	6-8, 17-19, 32-34, 40-45
Sept. 13	40, 43
Sept. 14	17, 34

Date	Plot numbers
	1972 - crop (continued)
Sept. 19	7, 8, 33
Sept. 21	6-8, 10, 17-19, 21, 32, 34, 36, 40-45
Oct. 2	17, 34
Oct. 5	6, 7, 19
	1973
April 11	1-45
June 4	1-45
June 11	4, 8, 10, 14, 18, 19, 36
June 12	16, 20, 21
June 13	1, 2, 6, 7, 12, 13, 15, 17, 32, 34, 35, 37-39
June 14	22-26
June 15	3, 5, 9, 11, 27-31, 33
June 19	14-16, 18, 19, 32, 35-39
June 20	1, 3, 4, 6-13, 34, 40, 43
June 21	20, 21, 29, 33
June 22	2, 5, 17, 22-28, 30, 31
June 25	41, 44
June 26	4, 6-11, 14-16, 18, 19, 21, 32, 34-37
June 27	2, 12, 13, 29, 38, 39
June 28	2, 5, 33
June 29	1, 4, 20, 30, 31, 36
July 2	17, 22-26
July 3	6-11, 14-16, 18, 19, 21, 27, 28, 32, 34-37
July 5	2, 12, 13, 29, 33, 38, 39
July 6	1, 3-5, 15, 20, 30, 31
July 9	41, 43, 44
July 10	2, 6-11, 29, 32, 34-36
July 11	12-14, 16-19, 21-26, 33, 37-39
	1974
May 25	9, 20, 23, 24, 35
June 7	9, 20, 23, 24, 35
June 17	9, 24
June 19	20
June 20	35
June 21	23
June 26	9, 24
July 1	20
July 5	23
July 8	24, 35
July 10	9
July 12	8, 12, 13, 25, 26, 34, 38, 39



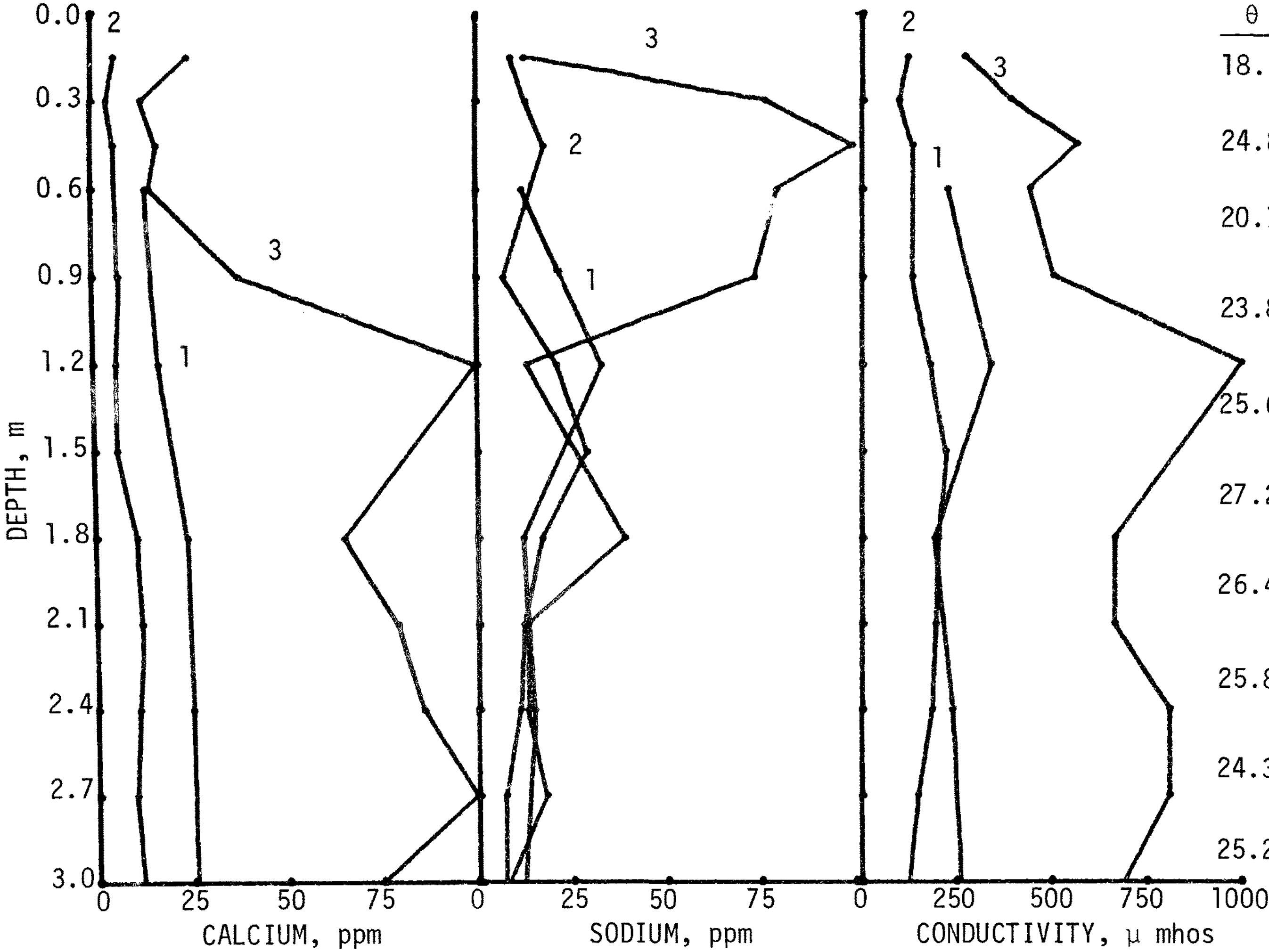
θ	CLAY, %	MATRIC POTENTIAL, cb
18.5	6	0
24.8	14	0
20.7	16	1
23.8	18	-2.0
25.6	33	2.1
27.2	34	-8.9
26.4	27	-2.9
25.8	26	-1.9
24.3	26	-16.9
25.2	36	-6.9

Figure 29. Concentrations of nitrate-N, chloride, and sulfate in a furrow-irrigated plot (Plot 20) in 1:1 extracts of core samples at the beginning of the growing season (curve 1) and end of growing season (curve 2) and in vacuum samples at the end of the growing season (curve 3), 1971.



θ	CLAY, %	MATRIC POTENTIAL, cb
18.5	6	0
24.8	14	0
20.7	16	1
23.8	18	-2.0
25.6	33	2.1
27.2	34	-8.9
26.4	27	-2.9
25.8	26	-1.9
24.3	26	-16.9
25.2	36	-6.9

Figure 30. Concentrations of magnesium, ammonium, and potassium in a furrow-irrigated plot (Plot 20) in 1:1 extracts of core samples at the beginning of the growing season (curve 1) and end of growing season (curve 2) and in vacuum samples at the end of the growing season (curve 3), 1971.



θ	CLAY, %	MATRIC POTENTIAL, cb
18.5	6	0
24.8	14	0
20.7	16	1
23.8	18	-2.0
25.6	33	2.1
27.2	34	-8.9
26.4	27	-2.9
25.8	26	-1.9
24.3	26	-16.9
25.2	36	-6.9

Figure 31. Concentrations of calcium, sodium, and conductivity in a furrow-irrigated plot (Plot 20) in 1:1 extracts of core samples at the beginning of the growing season (curve 1) and end of growing season (curve 2) and in vacuum samples at the end of the growing season (curve 3), 1971.

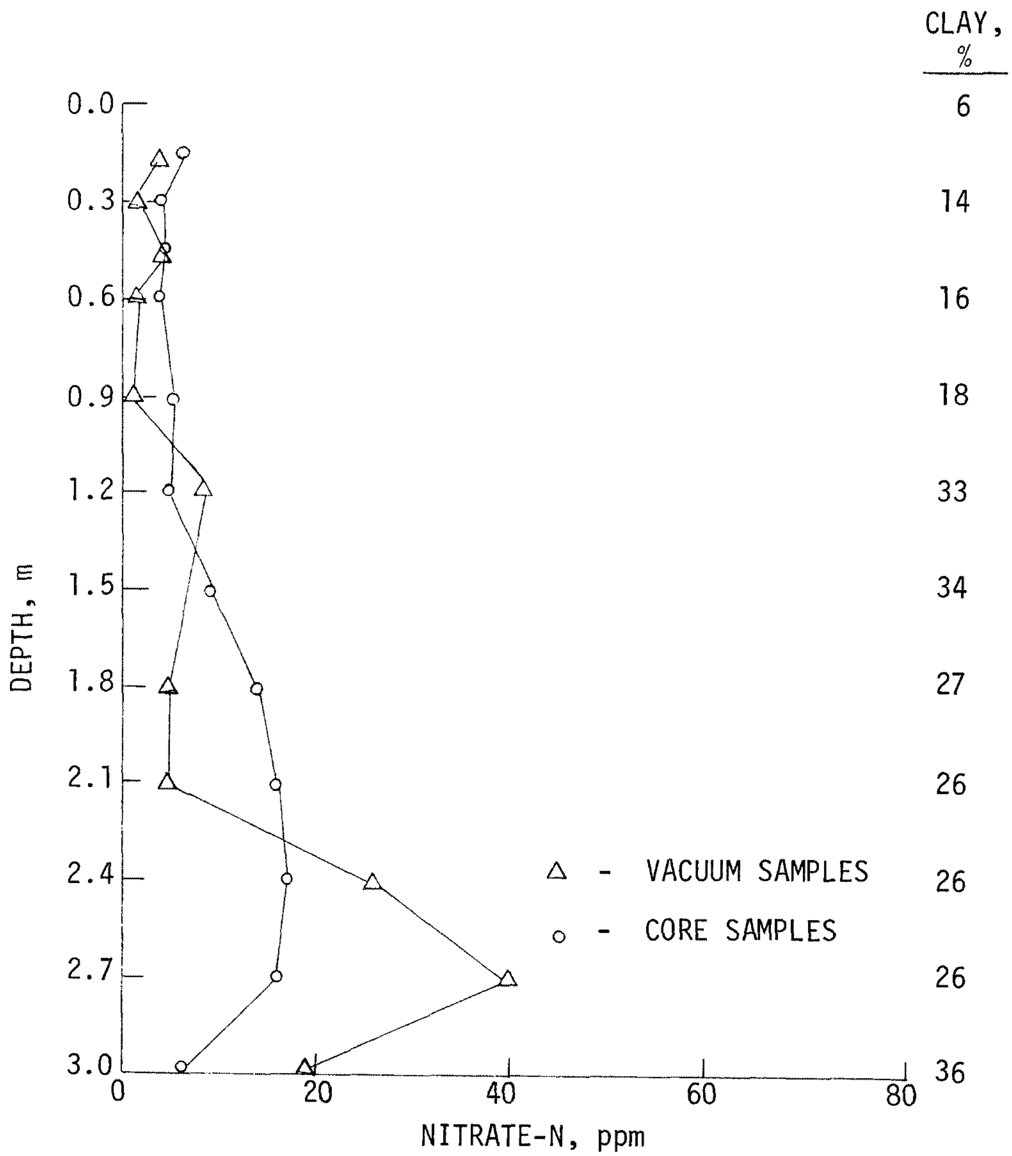


Figure 32. Comparison of nitrate-N concentrations of vacuum soil-water samples and 1:1 extracts of soil samples for various depths, Plot 20, Location 1. Field site near Munday, Texas, 1971.

Peak ion concentrations measured in the vacuum extract are somewhat related to soil characteristics. Both the 1.2- and 2.7-m concentration peaks of most of the ions are immediately above clay layers and are in zones of low matric potential. The presence of peak anion concentrations in the soil solution at these depths indicates poor leaching from the layers. These data indicate that 1:1 extracts may not adequately represent ion concentrations in the field as affected by soil physical conditions.

Kissel (11) has published relative to the small pore and large pore leachate. If his work can be extrapolated to these coarser-textured soils, it might be possible that the soil-water extracts give an index as to that portion of the soil solution in the large pores in which most of the ion movement takes place. This portion of the soil solution may in no way be representative of the bulk solution and may involve only a small portion of the soil water. However, this may be the dynamic portion of the soil water which contributes to degrading the quality of irrigation return flows.

The bulk solution is apparently less dynamic but is more representative of the toal salts in the soil. Leaching is apparently slower in bulk solution than in the vacuum-sampled solution.

Due to the major differences obtained, it was decided to further compare the vacuum and core studies in 1972. The results of these studies follow.

Comparison of Vacuum and Core Samples During 1972--

Sampling during the growing season--In 1971, some questions remained unanswered following the comparison of vacuum and core samples. In 1972, sprinkler-irrigated (Plot 10), furrow-irrigated (Plot 21), and subirrigated (Plot 36) plots were simultaneously core-sampled and vacuum-sampled at various times during the growing season. The objectives of the study were to compare the sampling techniques as indicators of ion movement and evaluate the possibility of using bromide as an indicator of nitrate movement. Bromide was chosen because of its low toxicity to plants and low concentration in soil and irrigation water.

Vacuum was used to extract samples through porous bulbs located at various depths beneath the tops of the beds in two locations of each plot. For comparison purposes, 2.5-cm diameter core samples were also taken in 15-cm increments from the tops of adjacent beds to depths of 300 cm.

After initial sampling to determine background concentrations of nitrate-N, bromide and chloride, granular sodium nitrate and sodium bromide were mixed and chiseled into the sides of the beds (25 cm from the center of each bed) at nitrogen and bromide rates of 45 and 54 kg/ha, respectively. Sweet corn was planted.

Porous bulb samples and core samples were taken simultaneously after each rainfall or irrigation throughout the crop year. Moisture content of core samples was determined; and the samples were ground, extracted with equal weights of deionized water, and filtered through a pressure filtration apparatus. Ion concentrations of the 1:1 soil:water extracts were divided by the air-dry moisture percentages.

Samples taken prior to the bromide and nitrate applications showed that the bromide and nitrate applications were low. Bromide concentrations from core samples varied from 0.06 to 0.55 ppm, and porous bulb samples 0.4 to 3.5 ppm. Nitrate-N concentrations were somewhat higher in that the ranges for core samples and porous bulb samples were 0.6 to 6.4 ppm and

4 to 33 ppm, respectively. A discussion of the results from each irrigation system follows.

Sprinkler-irrigated plots--Data from the porous bulb samples were much more consistent than that of the cores. Bromide and nitrate-N data from the soil-water extracts prior to the bromide application and during the growing season are shown in Figure 33. It can be seen that the bromide peak was detected at 0.3, 0.9 and 1.2 m, respectively, 14, 35 and 47 days after bromide and nitrate applications.

The nitrate-N concentrations prior to nitrate and bromide applications and 14 days after application were approximately equal at 0.3 and 0.6 m and were not related to the bromide concentrations indicating the nitrate was from soil nitrogen. The nitrate-N concentrations decreased at 0.3 and 0.6 m 35 days after application and further decreased at 0.9 m 47 days after application but increased at 1.2 and 1.5 m. The bromide moved from 0.3 to 1.2 m during the course of the growing season due to the addition of rainfall and irrigation water. Nitrate, on the other hand, decreased between 0 and 0.9 m due to crop utilization but increased at 1.2 and 1.5 m due to leaching. The peaks for bromide and nitrate below 0.6 m were qualitatively related.

The only date in which the bromide and nitrate-N concentrations of core samples were higher than those obtained prior to bromide and nitrate applications was 35 days after application (Figure 34). Bromide and nitrate-N concentration peaks occurred at 0.6 m in the core samples (Figure 34) compared to the peaks at 0.9 m of the vacuum samples (Figure 33). This suggests the sample obtained through the porous bulbs may have been obtained from a large area which included ions from the 0.6-m zone. Another possibility is that the movement in the row with the porous bulbs was different from the row from which the core samples were obtained.

Furrow-irrigated plots--The data from the furrow-irrigated plots were unique in two respects. The bromide and nitrate-N concentrations were higher than from the other two irrigation systems. Further, there was closer qualitative agreement between the core and vacuum samples. Figure 35 shows the vacuum bromide and nitrate-N concentrations. The data obtained after bromide and nitrate applications show good qualitative correlation between bromide and nitrate. Peak concentrations did not occur below 0.9 m while they were at 1.2 m in the sprinkler-irrigated plots (Figure 33). Ion concentrations of the core samples as the season progressed are given in Figure 36. The same qualitative relationships existed as were found with the vacuum samples, but the relative concentrations were not as high.

Subirrigated plots--Neither the bromide nor nitrate-N concentrations were very high in the subirrigated plots throughout the growing season. In only two of the measurements did the bromide concentrations obtained during the growing season exceed the concentrations obtained prior to the application of the bromide. These data are shown in Figure 37. It can be seen that peak concentrations of bromide in the vacuum extracts occurred at 0.6 m at 25 and 42 days after application and at 1.2 and 0.9 m, respectively, in

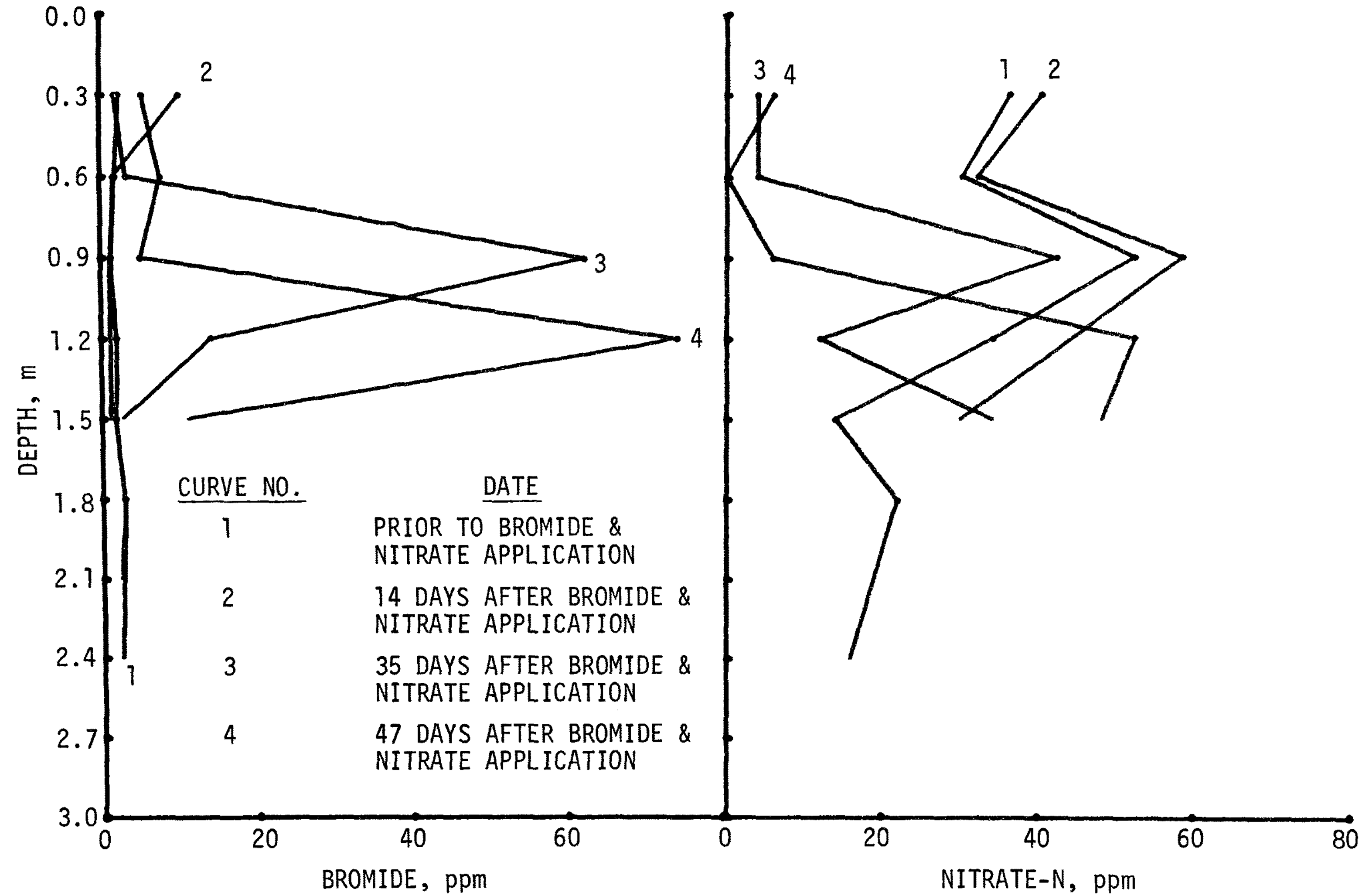


Figure 33. Concentrations of bromide and nitrate-N in porous bulb soil-water extracts obtained from the sprinkler-irrigated plots, 1972.

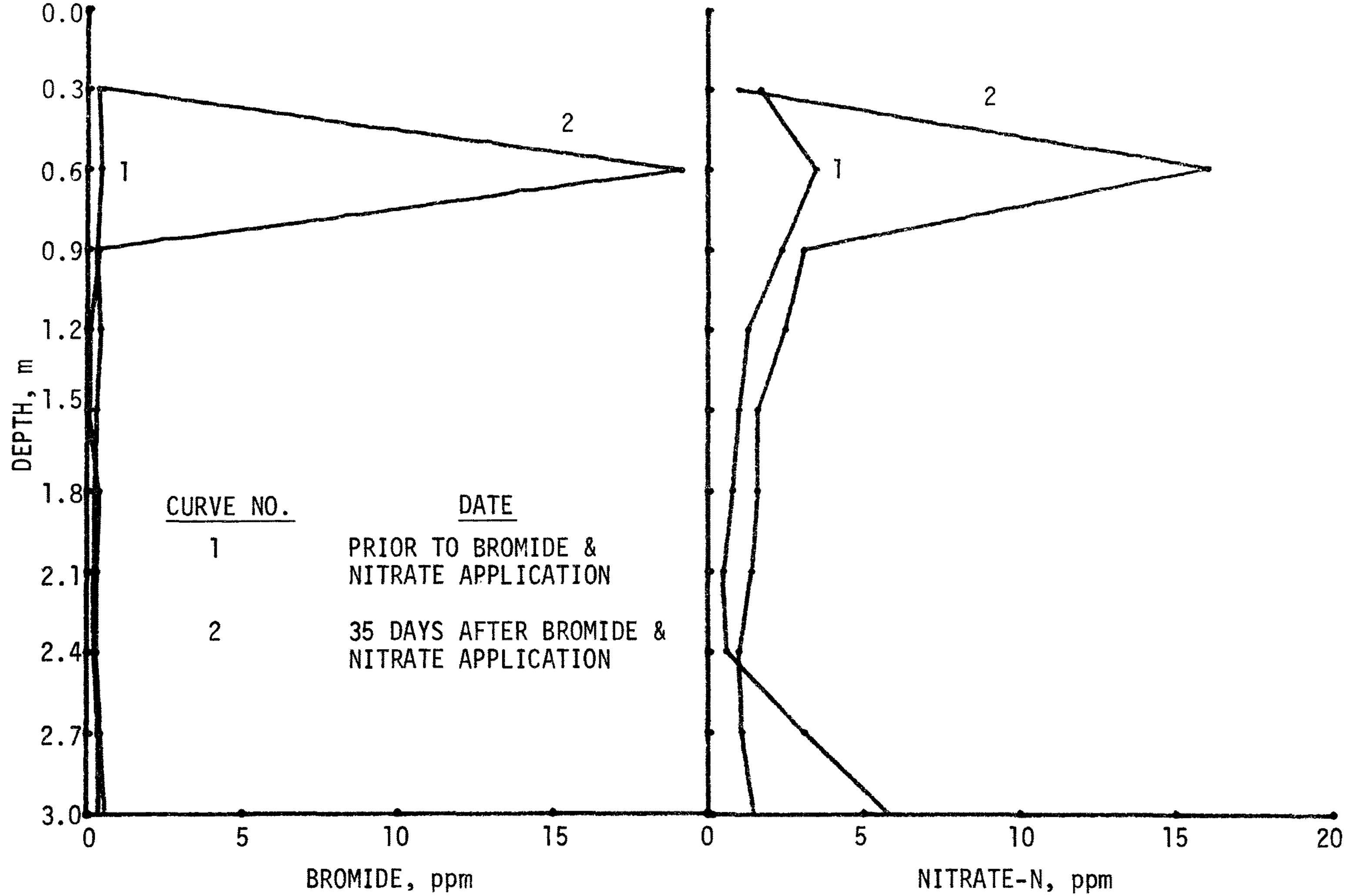


Figure 34. Concentrations of bromide and nitrate-N in 1:1 extracts of core samples obtained from the sprinkler-irrigated plots, 1972.

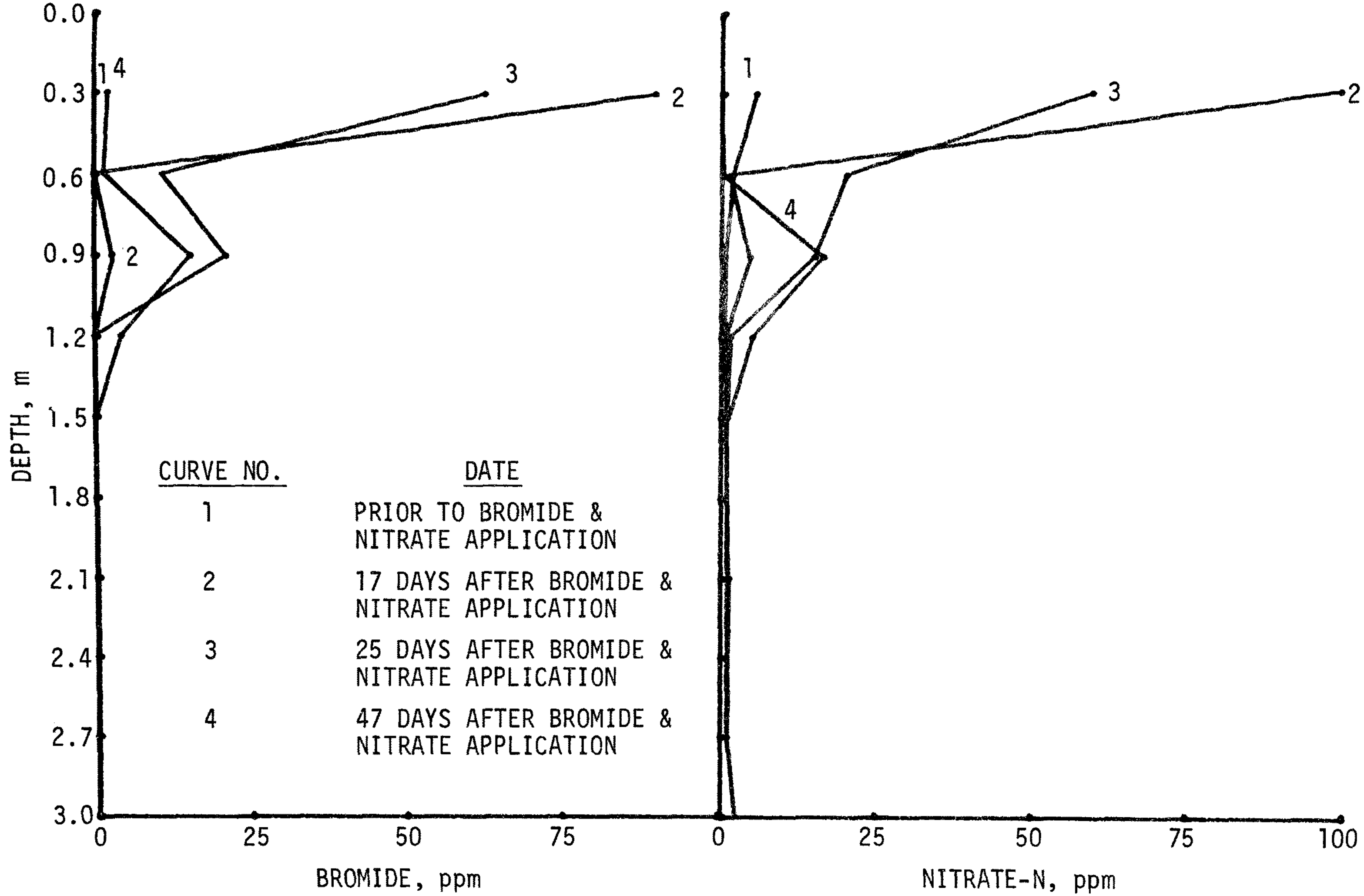


Figure 35. Concentrations of bromide and nitrate-N in porous bulb soil-water extracts from the furrow-irrigated plots, 1972.

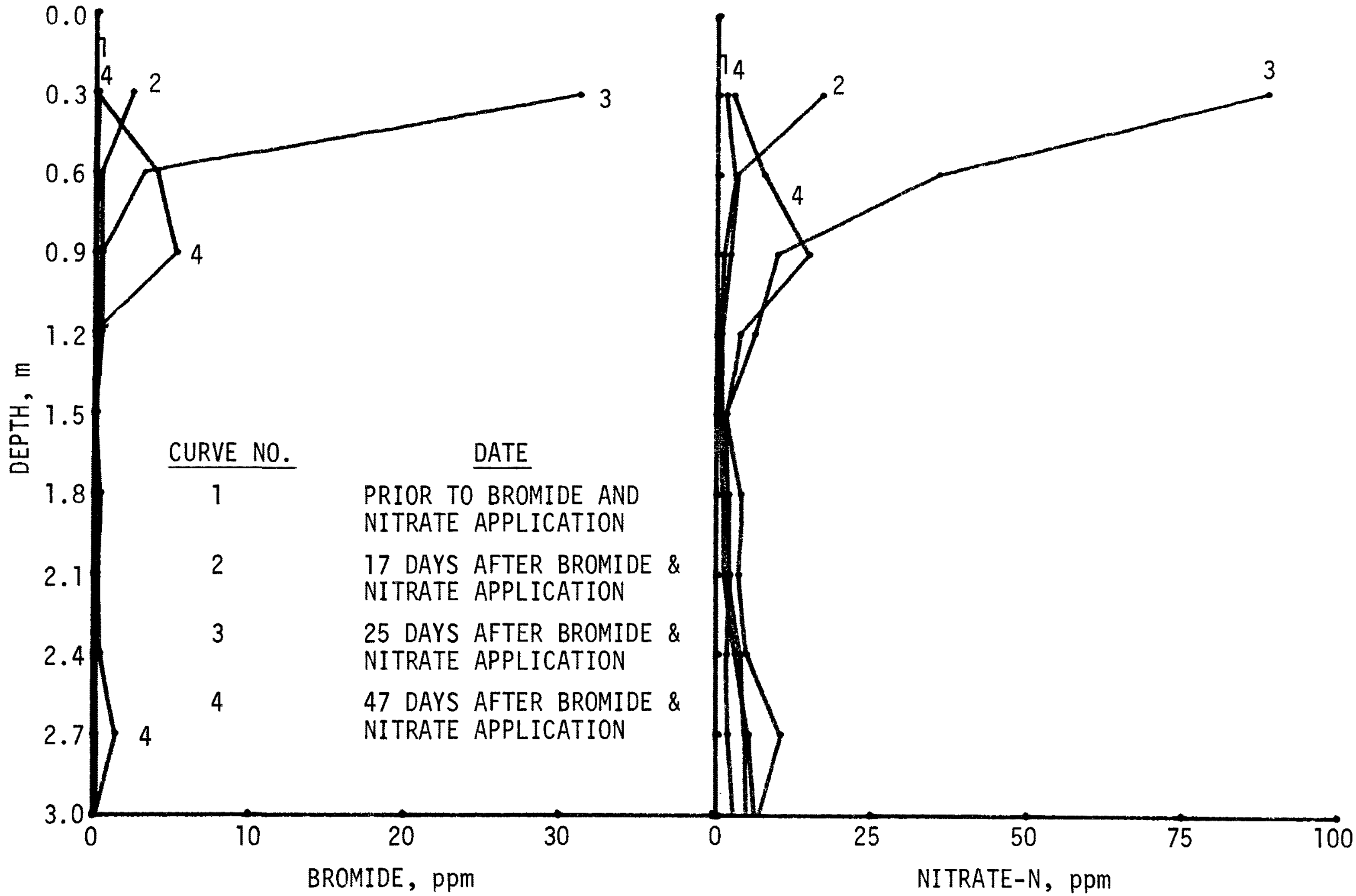


Figure 36. Concentrations of bromide and nitrate-N in 1:1 extracts of core samples obtained from the furrow-irrigated plots, 1972.

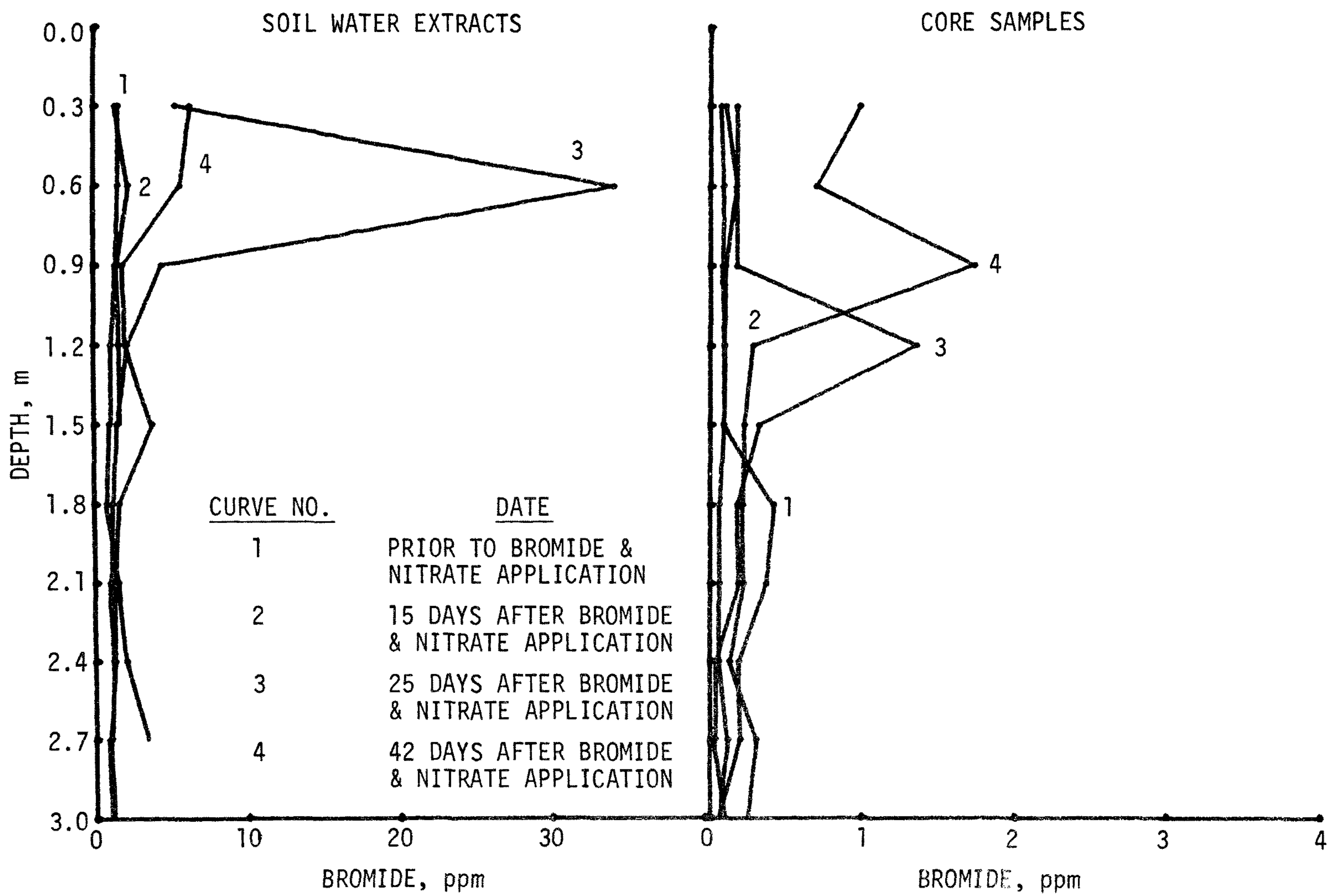


Figure 37. Concentration of bromide in porous bulb soil-water extracts and 1:1 extracts of core samples obtained from the subirrigated plots, 1972.

the core samples so there was little agreement between the core samples and soil-water extracts. This is probably due to the fact that different beds were used for soil-water extracts and core samples, and more variation as water movement occurred under the subirrigation system.

In no case was the nitrate-N content of either the soil-water extracts or the cores higher than those obtained prior to fertilizer application. Thus, nitrates were not detected with either sampling method.

Chloride concentrations in all systems--Chloride concentrations in the vacuum samples at the beginning and later in the growing season are shown in Figure 38 along with the chloride concentration of the irrigation water. Concentrations higher than those in the irrigation water were found in the surface 0.9 m and tended to increase as the season progressed. This was probably a result of concentration due to evaporation and leaching by rainfall. Concentrations were highest below 0.6 m in the furrow-irrigated plots followed by the sprinkler-irrigated and subirrigated plots. This held true throughout the growing season indicating that the quality of irrigation return flows would be better from subirrigation systems than the other two systems. The amounts of water applied in the sprinkler irrigation, furrow irrigation, and subirrigation systems in this study were 21.59, 27.92, and 24.13 cm, respectively. Therefore, the differences in concentration were probably due to the differences in water movement in the irrigation systems rather than the amount of water applied. Chloride concentrations in the surface 0.6 m were highest in the sprinkler-irrigated system followed by the furrow and subirrigation systems.

Data obtained from the core samples at the beginning of the season and toward the end of the growing season are shown in Figure 39. Major increases in chloride occurred in the surface 0.9 m in the furrow and sprinkler irrigation systems while only small changes occurred in the subirrigation system. Concentrations below the root zone were generally low (<10 ppm) which is too low to be of concern.

Sampling at the end of the growing season--Since major differences occurred in the data obtained from the different irrigation systems during the growing season, it was decided to obtain a detailed cross-section of bromide, nitrate-N, and chloride concentrations at the end of the growing season to determine the fate of bromide and nitrate bands applied to each irrigation system.

Soil core samples 2.5 cm in diameter and 30 cm long were taken at 13-cm intervals laterally from one bed to an adjacent bed (102 cm) to depths of 210 cm. Results are shown in Figures 41 through 46. The cross-sections show the actual location of the bands of bromide and nitrate-N. Chloride concentrations indicate the extent and location of the season's irrigation water (see Key, Figure 40).

In Location 1 of the sprinkler-irrigated plot (Figure 41), bromide was found as two distinct bands directly below the application sites in the sides of the beds. Nitrate-N concentrations were low in the area of

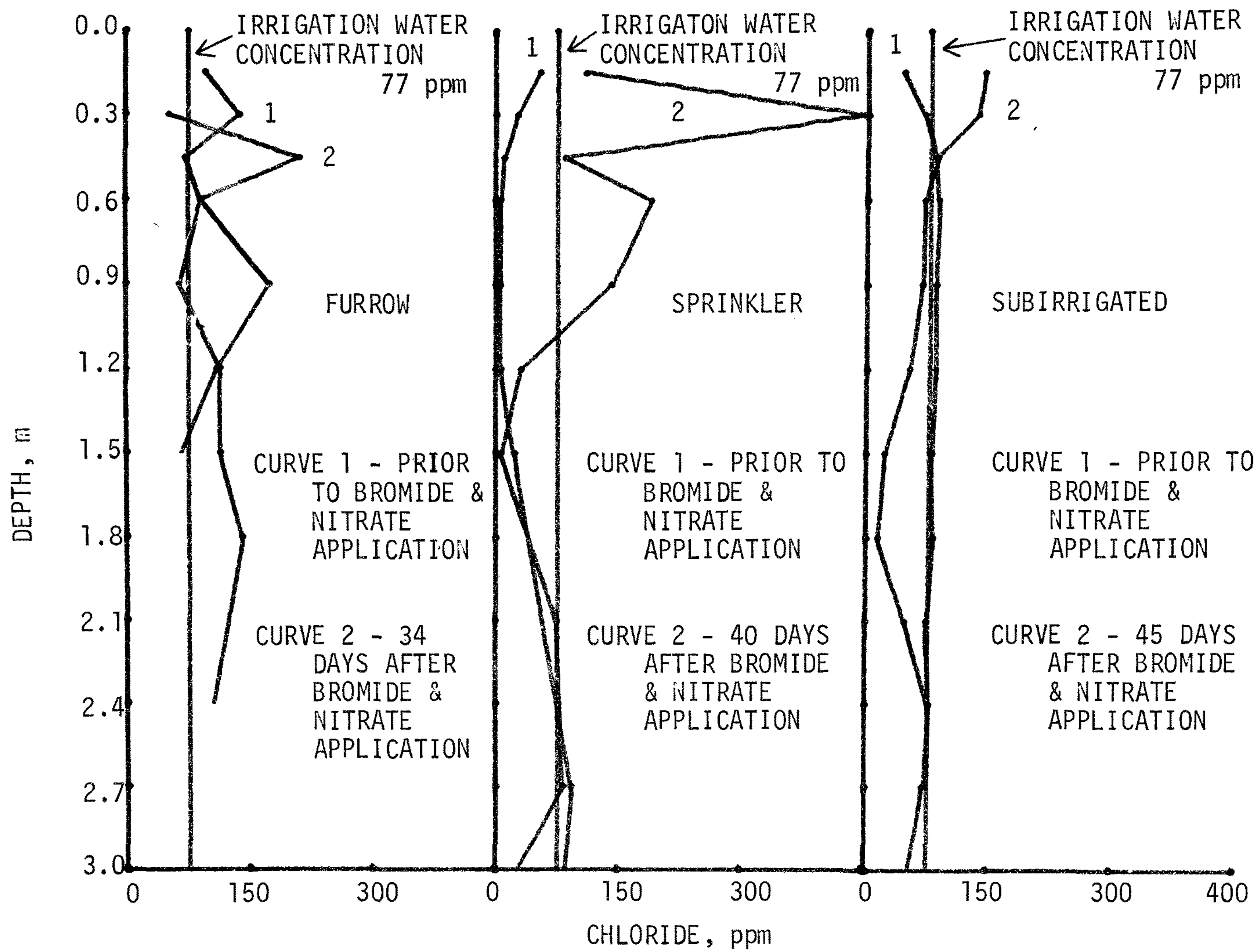


Figure 38. Concentration of chloride in porous bulb soil-water extracts of samples obtained from furrow, sprinkler, and subirrigated plots, 1972.

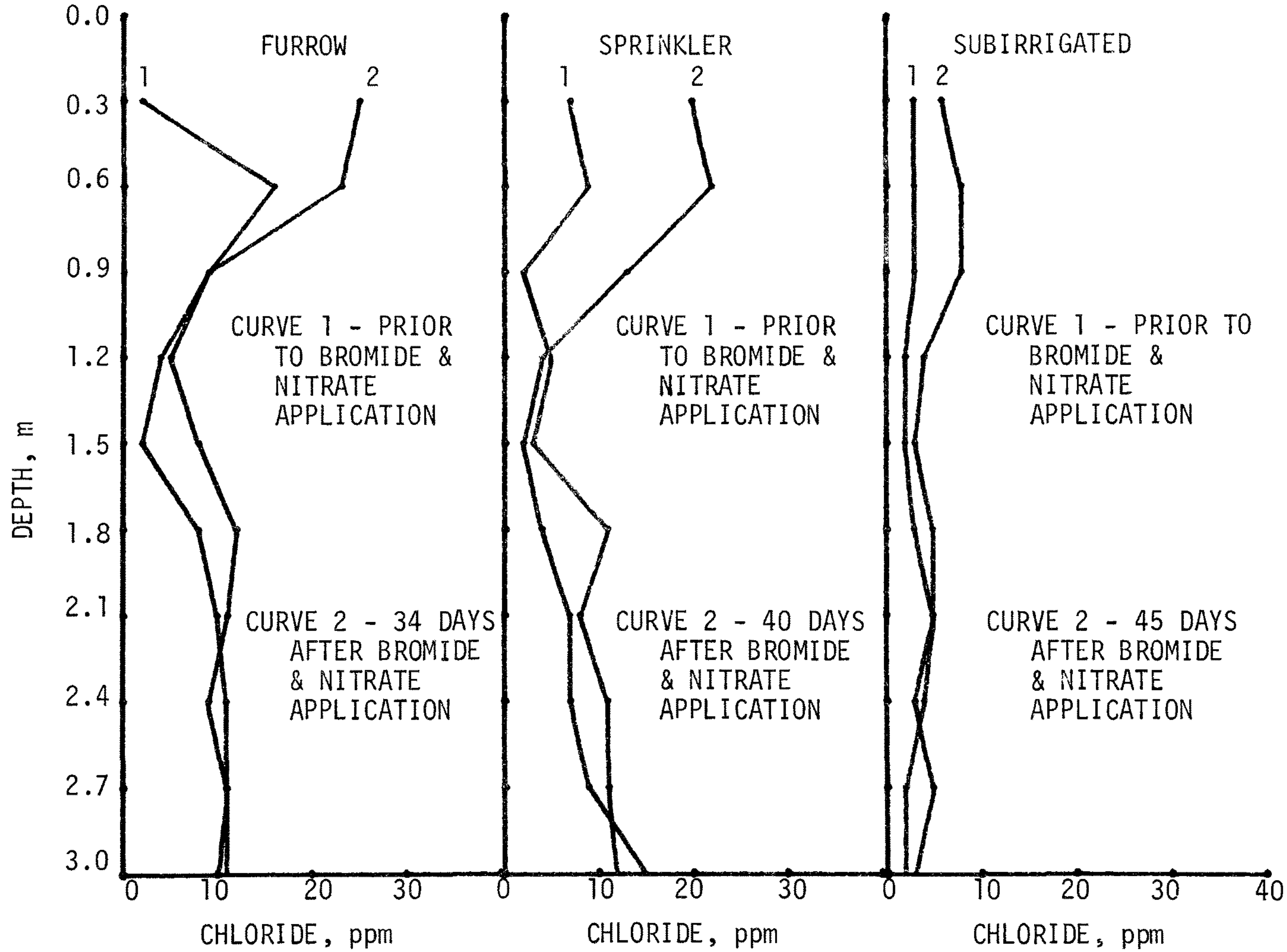


Figure 39. Concentrations of chloride in 1:1 extracts of core samples obtained from the furrow, sprinkler, and subirrigated plots, 1972.

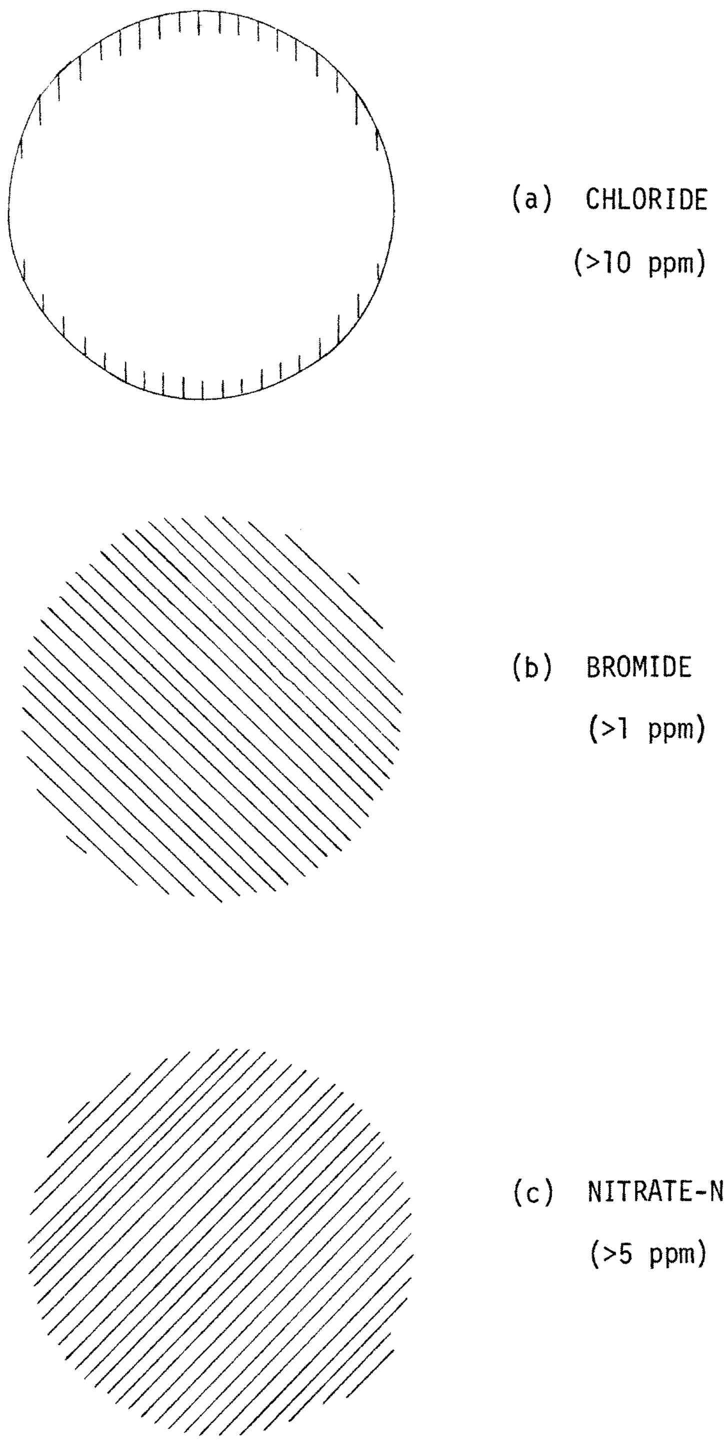


Figure 40. Symbol key for Figures 41 through 46.

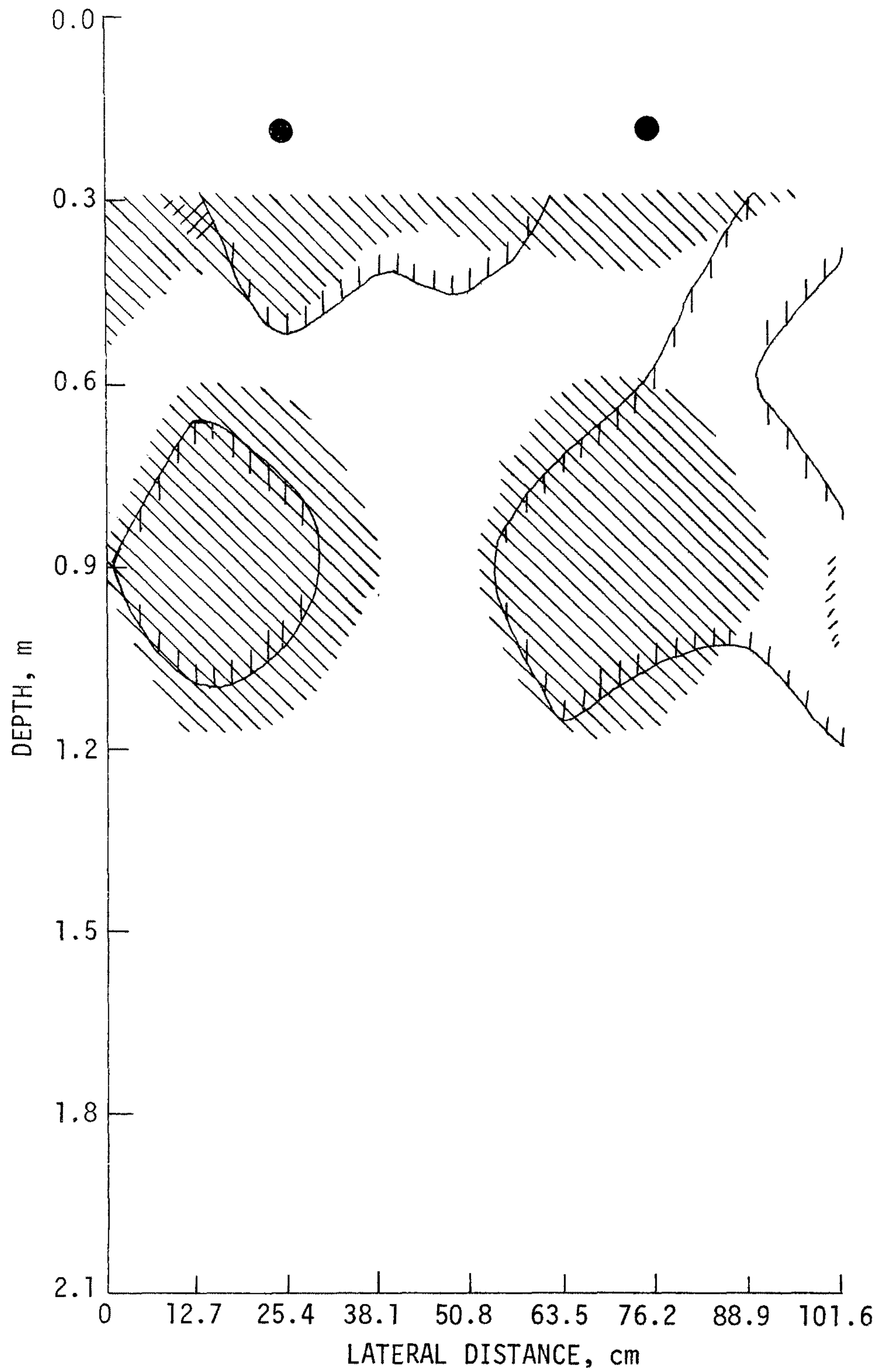


Figure 41. Areas of significant concentrations of bromide, nitrate-N, and chloride in a sprinkler-irrigated plot (Plot 10-1) 81 days after application of bromide, 1972. (See Figure 40 for symbol key)
● - Original location of fertilizer band.

high bromide concentrations indicating that the nitrogen was used by the crop when the bands were higher in the profile.

In the other sampling location of the sprinkler plot (Figure 42), the bromide bands grew more diffuse as they moved downward to depths of 1.8 to 2.1 m. High nitrate-N concentrations were found within each bromide band, indicating that the nitrogen bands were leached from the root zone before they could be used by the crop.

The fertilizer bands, although still apparent, were much more diffuse in the furrow-irrigated plots than in the sprinkler-irrigated plots (Figures 43 and 44). Furrow-applied water moved material toward the beds and down and maximum bromide and nitrate-N concentrations were found below the tops of the beds in Location 1. Lateral movement of the bands over a restricting layer is indicated in Location 2 of the furrow plot. Both locations of the furrow plot indicated nitrate-N leaching losses.

Erratic results were obtained in Location 1 of the subirrigated plot and were probably a function of the sampling location relative to the emitters of the laterals (Figure 45). One fact is obvious: although there were no restricting layers and water moved freely through the upper 2.5 m of the profile, subirrigation had kept applied nitrate-N and bromide in the surface 0.9 to 1.2 m. A logical pattern of chloride accumulation around the laterals of Location 2 (Figure 46) is apparent. Bromide was moved from the point of application toward the furrow and was still located in the upper 0.75 m. As with the sprinkler system, when bromide was held in the surface 0.90 m, nitrate-N was not detected.

Summary and Conclusions--

The three different irrigation systems provided three distinct patterns of irrigation water and fertilizer band movement (Figures 41 through 46):

1. Water applied through sprinkler systems and rain tends to move the banded material straight down. Some of this may be obtained by a vacuum system (Figure 33) but may be missed by core sampling unless it diffuses into the center of the bed.

2. Furrow-applied irrigation water concentrates the bands in the plane of the bulbs.

3. Subirrigation water concentrates the bands in the top of the bed away from the porous bulbs. Water flow was radially outward, carrying fertilizer salts away from the sampling area in the root zone.

Cross-sectional core sampling, although much slower and more tedious, proved to be a better method of sampling. Actual location and concentrations of the bands were determined by this method in most cases, while single-plane porous bulb samples indicated higher concentrations in the root zones of furrow plots and lower concentrations in sprinkler and subirrigated plots.

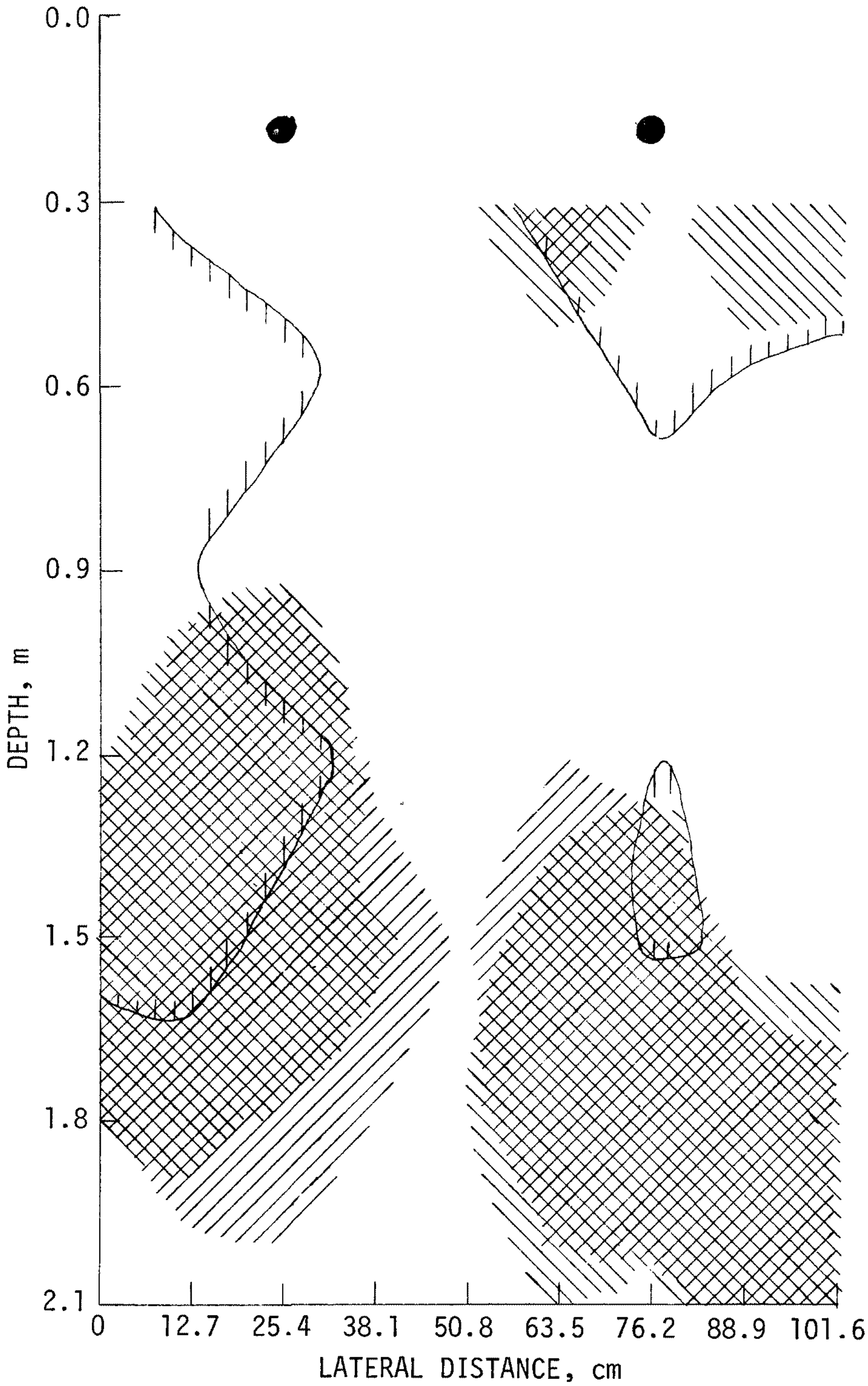


Figure 42. Areas of significant concentrations of bromide, nitrate-N, and chloride in a sprinkler-irrigated plot (Plot 10-2) 81 days after application of bromide, 1972. (See Figure 40 for symbol key)
● - Original location of fertilizer band.

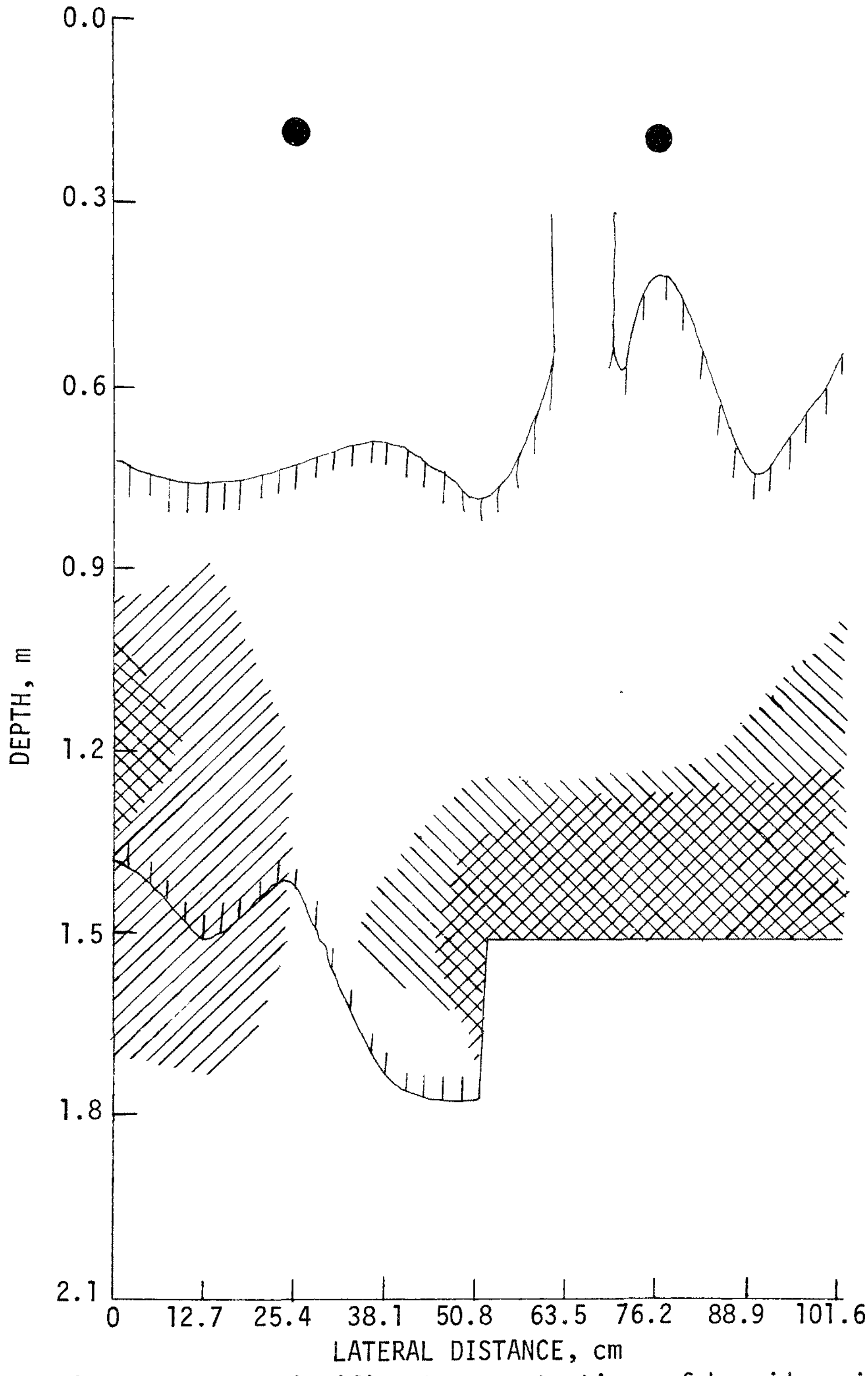


Figure 43. Areas of significant concentrations of bromide, nitrate-N, and chloride in a furrow-irrigated plot (Plot 21-1) 81 days after application of bromide, 1972. (See Figure 40 for symbol key) ● - Original location of fertilizer band.

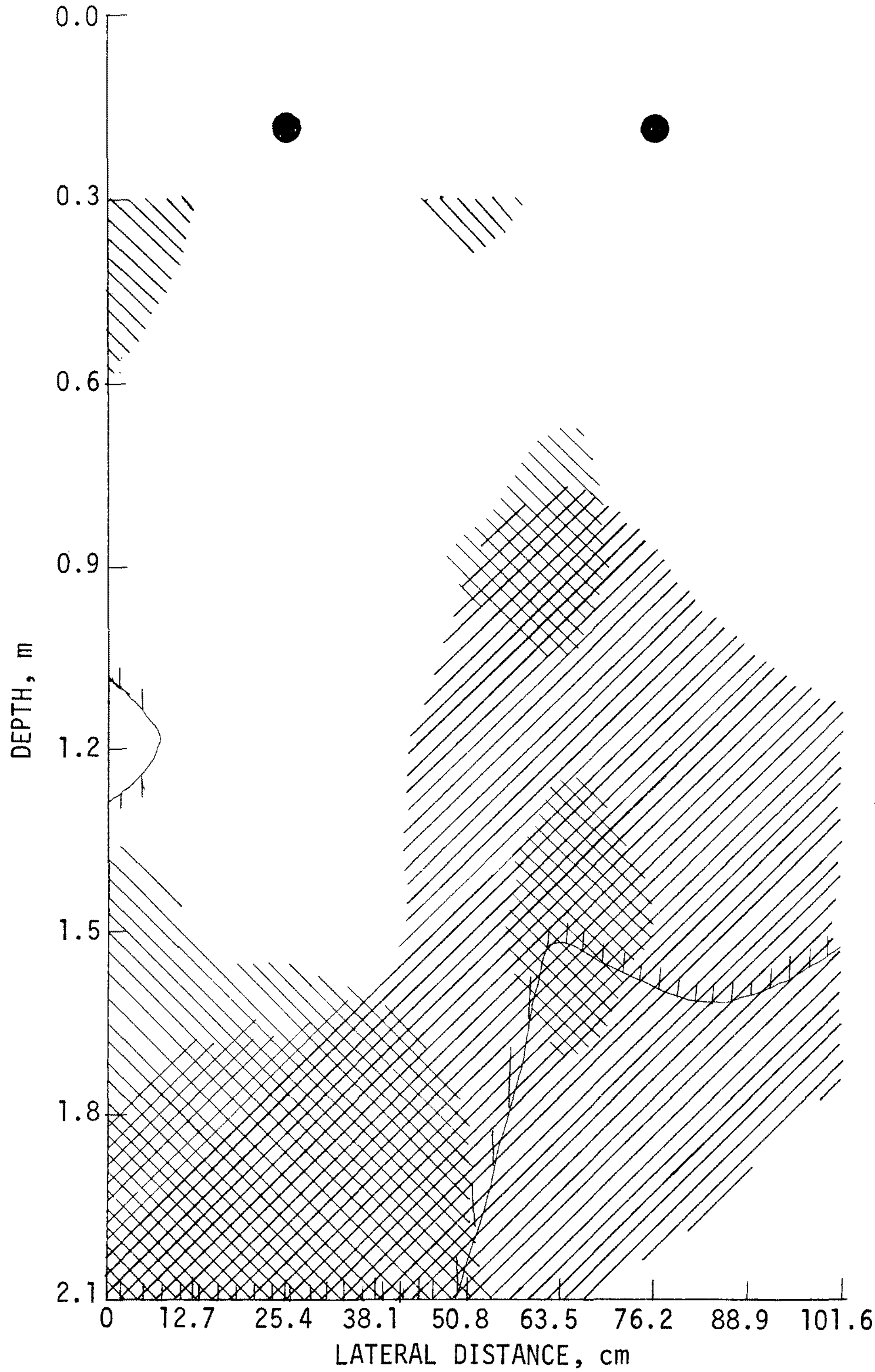


Figure 44. Areas of significant concentrations of bromide, nitrate-N, and chloride in a furrow-irrigated plot (Plot 21-2) 81 days after application of bromide, 1972. (See Figure 40 for symbol key) ● - Original location of fertilizer band.

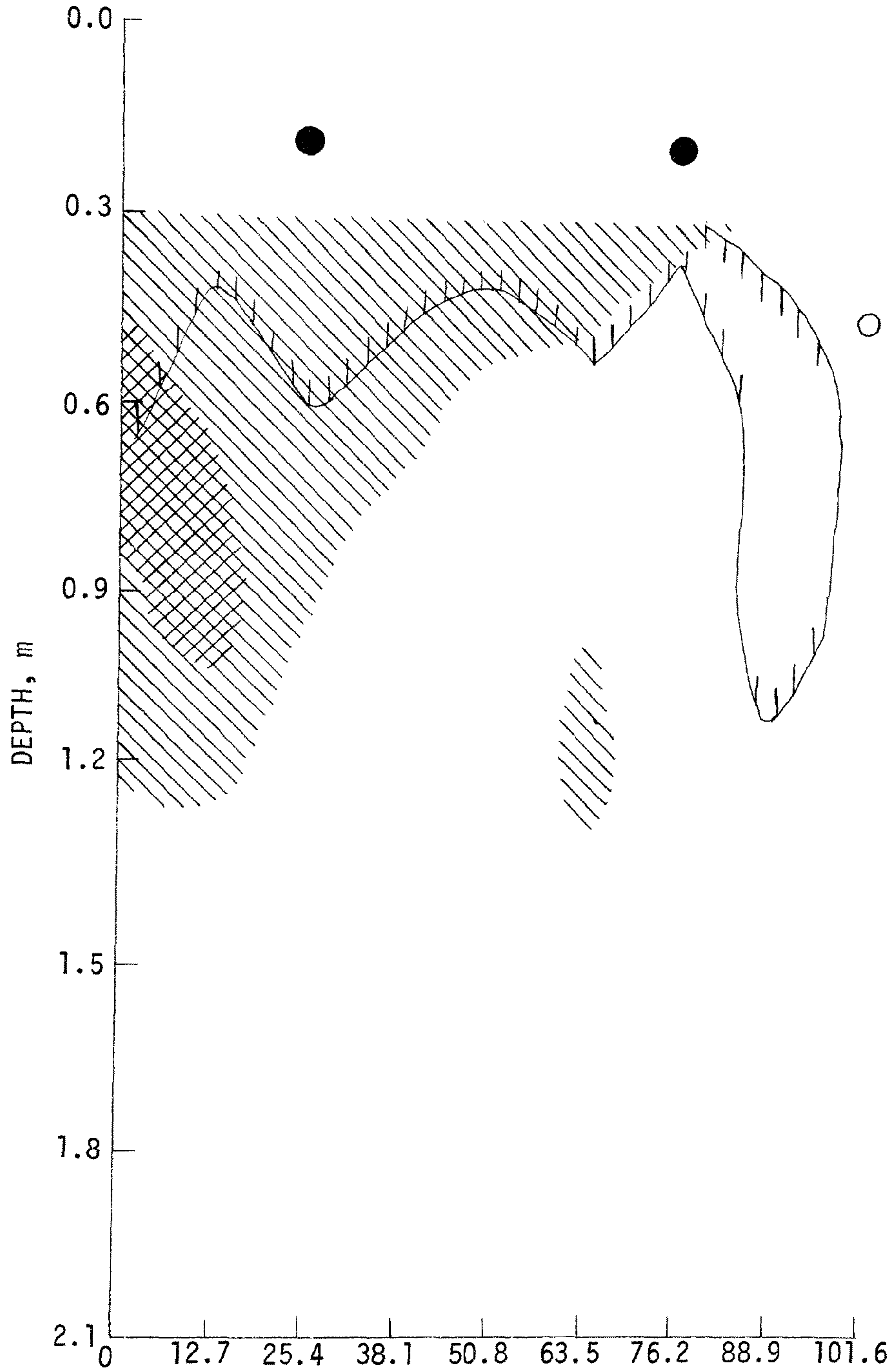


Figure 45. Areas of significant concentrations of bromide, nitrate-N, and chloride in a subirrigated plot (Plot 36-1) 81 days after application of bromide, 1972. (See Figure 40 for symbol key) ● - Original location of fertilizer band. ○ - Subirrigation pipe.

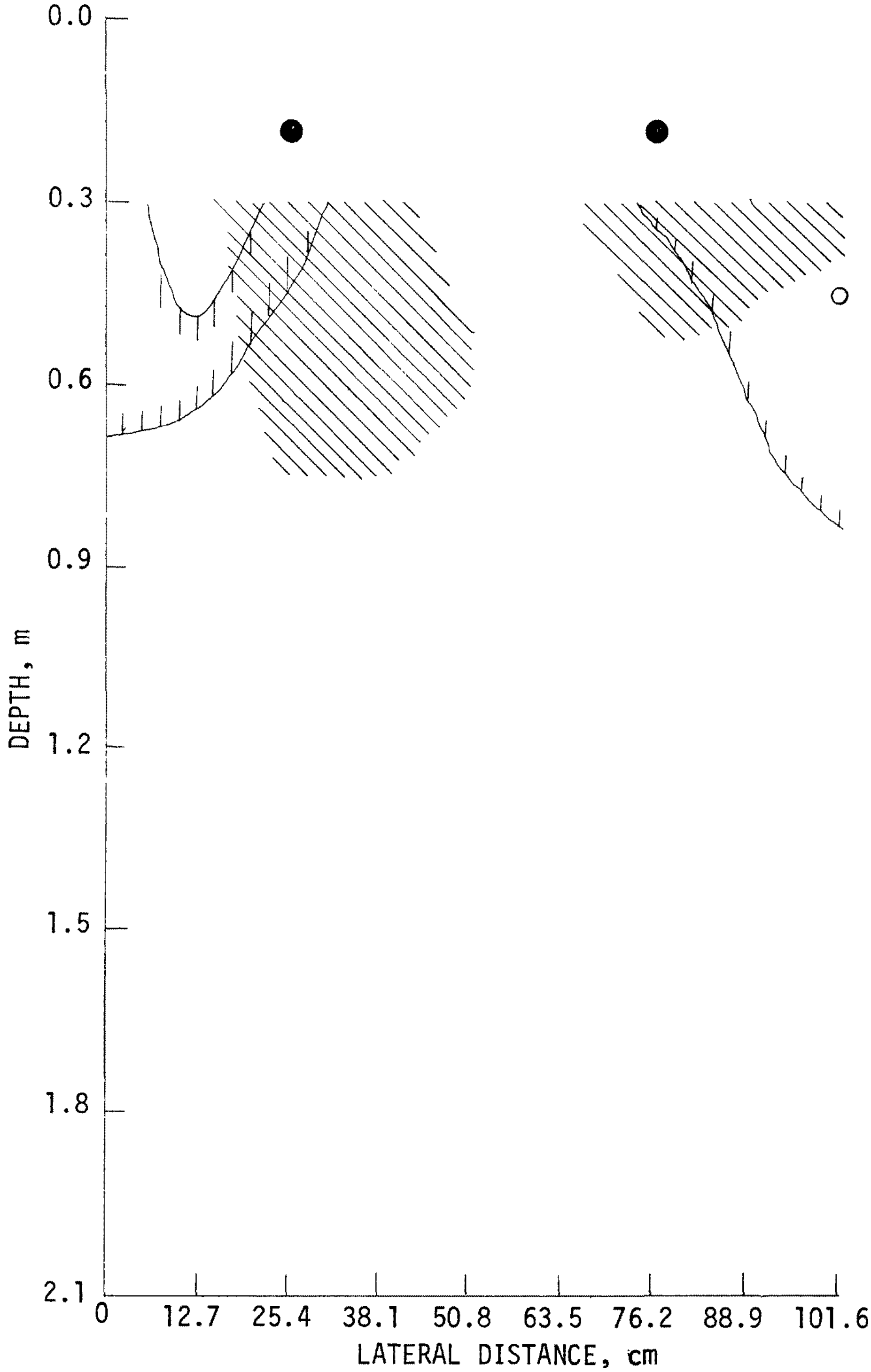


Figure 46. Areas of significant concentrations of bromide, nitrate-N, and chloride in a subirrigated plot (Plot 36-2) 81 days after application of bromide, 1972. (See Figure 40 for symbol key) ● - Original location of fertilizer band. ○ - Subirrigation pipe.

Porous bulbs sample a larger area and would provide better sampling under situations where the fertilizer is broadcast rather than banded. The data from porous bulbs are better related to what the quality might be expected in the water from irrigation return flows than the data from core samples. However, it is often difficult to obtain consistent porous bulb data.

LUBBOCK LOCATION

Although the subirrigation system (described in Section 4) was installed in March, the automation was not completed until July. Sweet corn which was planted May 16 was at the tassel stage of growth when the automation was completed. Four switching tensiometers 0.30 m in length in each of two plots were located 0.15 m to the side of orifices and were set at potentials of -30 cb and -60 cb. The amount of water applied to the two plots during the period the system was automated is shown in Table 18. During the six-day period from July 7 to July 12, 16.8 and 3.9 cm of water were applied to the -30 cb and -60 cb plots, respectively. Between July 12 and July 22, the system was inoperable due to the necessity of making changes in automation and flow control valves.

To obtain information concerning soil-water distribution, tensiometers were installed in late July at 0.10, 0.25, and 0.50 m from an orifice at two locations in each plot at different depths. Following installation, 2.8 cm of water were applied to each plot. From Figures 47 and 48, it can be seen that the primary zone of soil-water potential change following irrigation occurred below 0.15 m and above 0.90 m. In the -30 cb plot, the largest increase in potential occurred at 30 cm followed by 0.6 m. Changes in soil-water potential at 0.15, 0.9, and 1.2 m were negligible, indicating that there was still retention capacity in the soil profile for storage of rainfall following the irrigation. Corn in the -60 cb plot yielded 21,000 ears/ha and the -30 cb plot yielded 41,990 ears/ha. Corn in the -60 cb plot showed visual signs of stress while the -30 cb plot did not. This soil is underlain with a layer higher in clay content at 0.9 m, which may be a factor in maintaining a high potential under field conditions.

Changes in soil-water content on the same dates the changes in potential were measured are shown in Figure 49. It can be seen that major increases in soil-water content that occurred between August 3 and August 4 were not reflected in increases in soil-water potential at depths greater than 0.9 m in the -60 cb plot. The access tube for the neutron probe was 0.15 m from the subirrigation line in close proximity to but at a different location from the tensiometers located 0.1, 0.25, and 0.5 m from the irrigation line. It may have been possible that the soil-water content was different in the area of the access tube and the area where the tensiometers were located so that no relationship could be expected to exist.

Much better correlation was obtained in the -30 cb plot between the soil-water content (Figure 49) and soil-water potential (Figure 47). Changes in both parameters occurred throughout the profile. At the end of the six-day period, increases in soil-water content occurred in all

TABLE 18. CENTIMETERS OF IRRIGATION WATER APPLIED AUTOMATICALLY TO SUBIRRIGATION PLOTS AT LUBBOCK, TEXAS, DURING 1971

Date	Time	Total hours	Water applied, cm	Total, cm
	-30 cb plots Two 19-1pm Dole valves			
July 7-8	7:30 p.m. - 7:30 a.m.	12	2.84	
July 8-9	8:30 p.m. - 9:30 a.m.	13	2.99	
July 9-10	9:30 a.m. - 1:30 a.m.	16	3.78	
July 10	4:00 p.m. - 6:30 p.m.	2-1/2	0.48	
July 11	12:30 a.m. - 9:30 a.m.	9	2.13	
July 11-12	3:30 p.m. - 11:00 a.m.	19-1/2	4.62	
				16.84
	-30 cb plots Two 9.5-1pm Dole valves			
July 22	1:00 p.m. - 11:45 a.m.	22-3/4	2.69	
July 25-26	9:00 p.m. - 7:30 a.m.	10-1/2	1.24	
July 29	7:45 p.m. - 8:15 p.m.	1/2	0.05	
July 30	9:00 a.m. - 9:30 a.m.	1/2	0.05	
July 30	8:30 p.m. - 9:00 p.m.	1/2	0.05	
July 30-31	11:45 p.m. - 12:45 a.m.	1	0.10	
July 31	9:45 a.m. - 10:15 a.m.	1/2	0.05	
July 31	1:00 p.m. - 4:00 p.m.	3	0.36	
July 31	8:30 p.m. - 12:00 p.m.	3-1/2	0.41	
Aug. 3-4	11:00 a.m. - 11:00 a.m.	24	2.84	
				7.84
				24.68
	-60 cb plots Two 19-1pm Dole valves			
July 10	5:30 a.m. - 7:30 a.m.	2	0.46	
July 11-12	8:30 p.m. - 11:00 a.m.	14-1/2	3.43	
				3.89
	-60 cb plots Two 9.5-1pm Dole valves			
Aug. 3-4	11:00 a.m. - 11:00 a.m.	24	2.84	
				2.84
				6.73

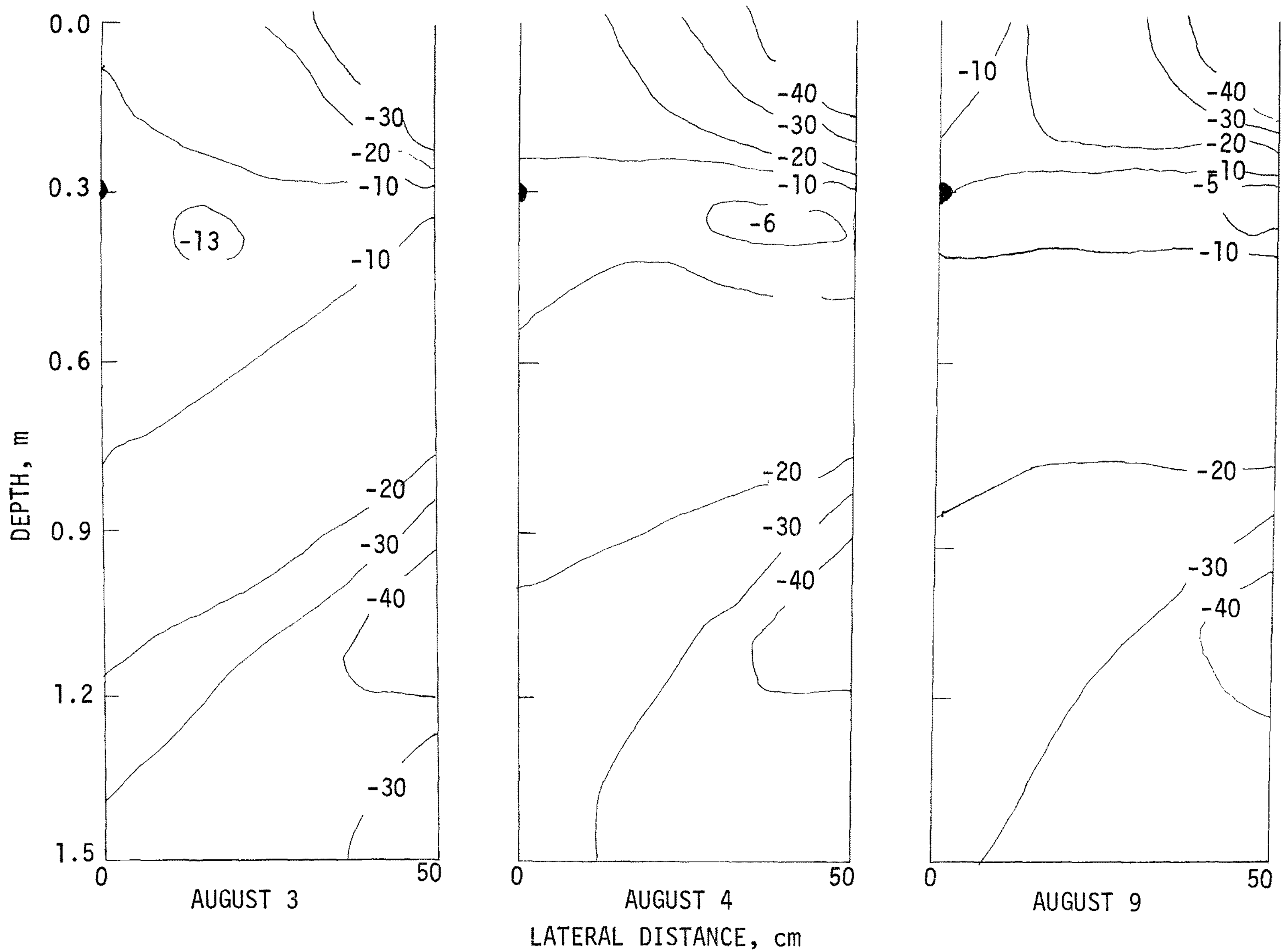


Figure 47. Soil-water potential (cb) on selected dates in the -30 cb plot before and after irrigating with 2.8 cm of water between August 3 and August 9 in 1971 at Lubbock, Texas. ◗ - subirrigation pipe.

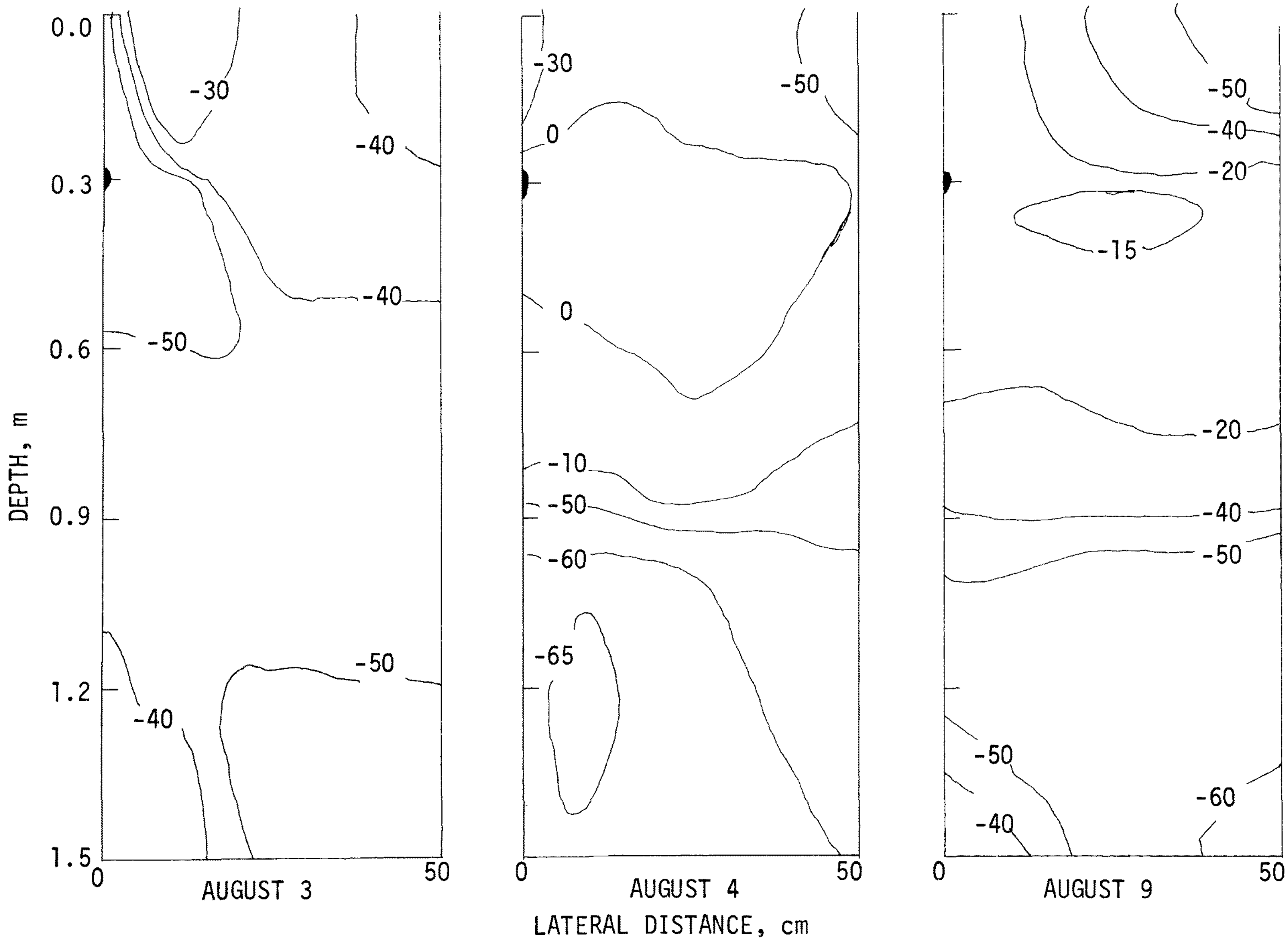


Figure 48. Soil-water potential (cb) on selected dates in the -60 cb plot before and after irrigating with 2.8 cm of water between August 3 and August 9 in 1971 at Lubbock, Texas. ◗ - subirrigation pipe.

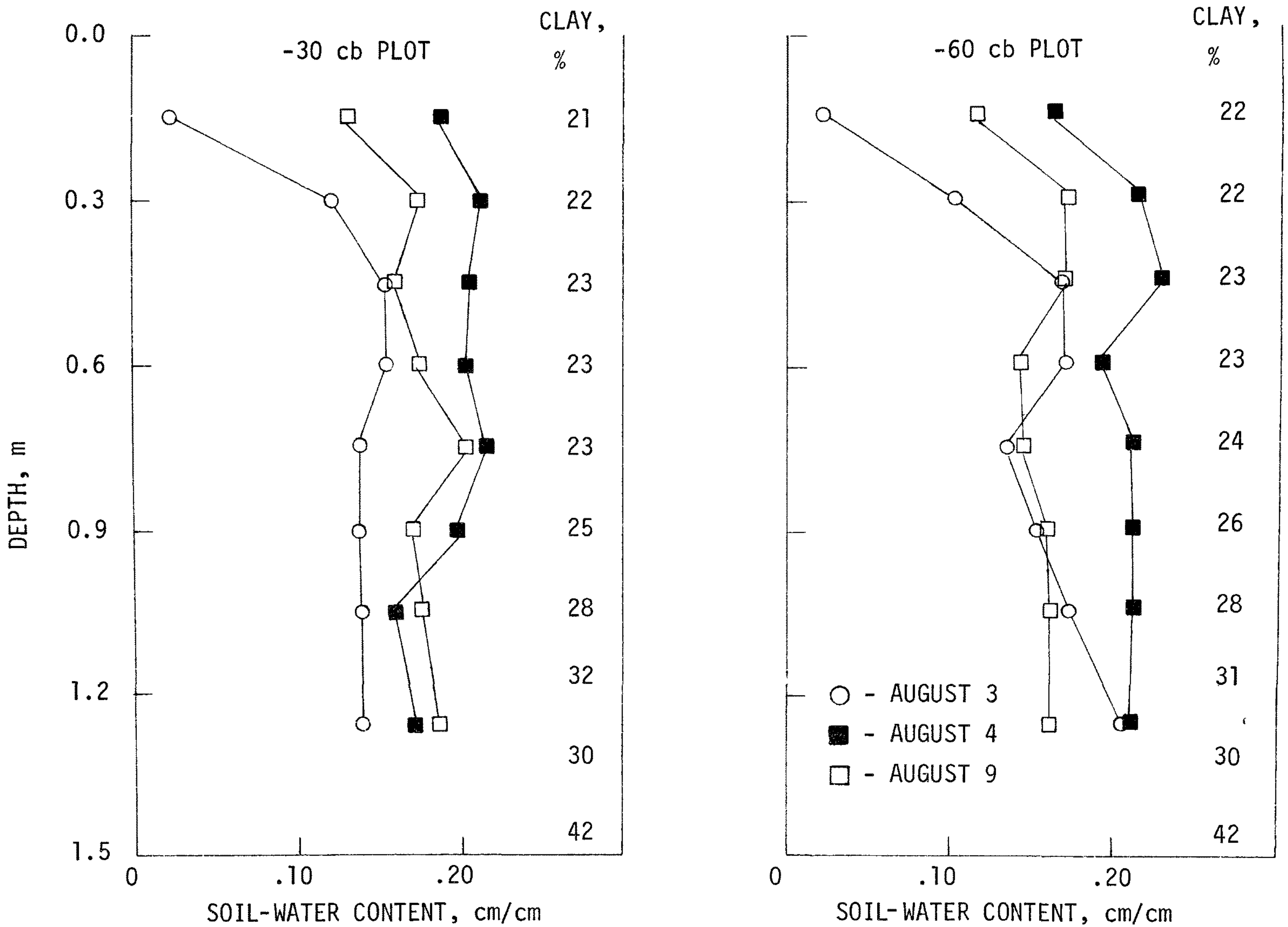


Figure 49. Soil-water content on selected dates before and after irrigation (2.8 cm of water applied between August 3 and August 9) in 1971 at Lubbock, Texas.

depths in the -60 cb plot while changes did not occur at 0.45, 0.75, 0.9, and 1.2 m in the -30 cb plot.

Since decreases in yield occurred with water stress in the -60 cb plot in 1971, the potential levels of the switching tensiometers were changed from -30 and -60 to -20 and -40 in 1972. Rainfall was above average (Table 19) and was evenly distributed throughout the growing season in 1972. Consequently, only 6.35 cm of irrigation water were added to the -20 cb plot, while the -40 cb plot received 7.72 cm (Table 20). The -40 cb plot yielded 66,720 ears/ha while the -20 cb plot yielded 59,300 ears/ha. The cumulative amount of water applied during the growing season compared to the potential ET as estimated by Jensen, et al. (10) is shown in Figure 50. During May, the total water received by each plot approximately equaled the potential ET.

During June, the slope of the cumulative rainfall curve was less than that of the potential ET curve showing that rainfall received was less than the ET potential by approximately 20 cm. The soil-water storage of these soils was adequate to supply this amount.

The studies from Lubbock during 1971 and 1972 indicate that the automated subirrigation systems apparently do have some of the advantages hypothesized in the initial project. It is necessary to maintain a low soil-water potential in only a portion of the profile to adequately supply crops with water. This leaves room in the soil profile to store water from rains. This could significantly increase water-use efficiency by minimizing the amount of water lost to irrigation return flows by making better use of rainfall and thus applying less irrigation water containing salts.

TABLE 19. RAINFALL RECEIVED AT LUBBOCK, TEXAS, BETWEEN THE EMERGENCE AND HARVEST OF THE 1972 CROP

Date	Amount, cm
April 29	0.23
Total	0.23
May 4	T
5	0.03
6	3.48
7	1.24
10	1.93
11	0.76
14	0.23
25	T
26	0.23
28	0.53
29	0.03
30	T
Total	8.46
June 11	2.01
13	5.18
14	0.94
15	0.89
17	0.66
22	0.05
29	0.71
30	0.15
Total	10.59
July 1	1.32
3	3.35
4	2.01
5	0.03
6	T
9	2.11
18	0.58
19	T
20	0.05
21	3.84
Total	13.29

TABLE 20. IRRIGATION WATER APPLIED AUTOMATICALLY TO SUBIRRIGATION PLOTS AT LUBBOCK, TEXAS, DURING 1972

Date	Water applied, cm	
	-20 cb Plot	-40 cb Plot
April 20	1.09	1.09
28	1.14	1.14
May 1	1.14	1.14
June 21	0.36	
23		1.30
24	0.25	0.76
25	0.66	
26	0.33	
27		2.24
28	0.79	
July 1	0.38	
3		0.69
17	0.33	
Total	6.47	8.36

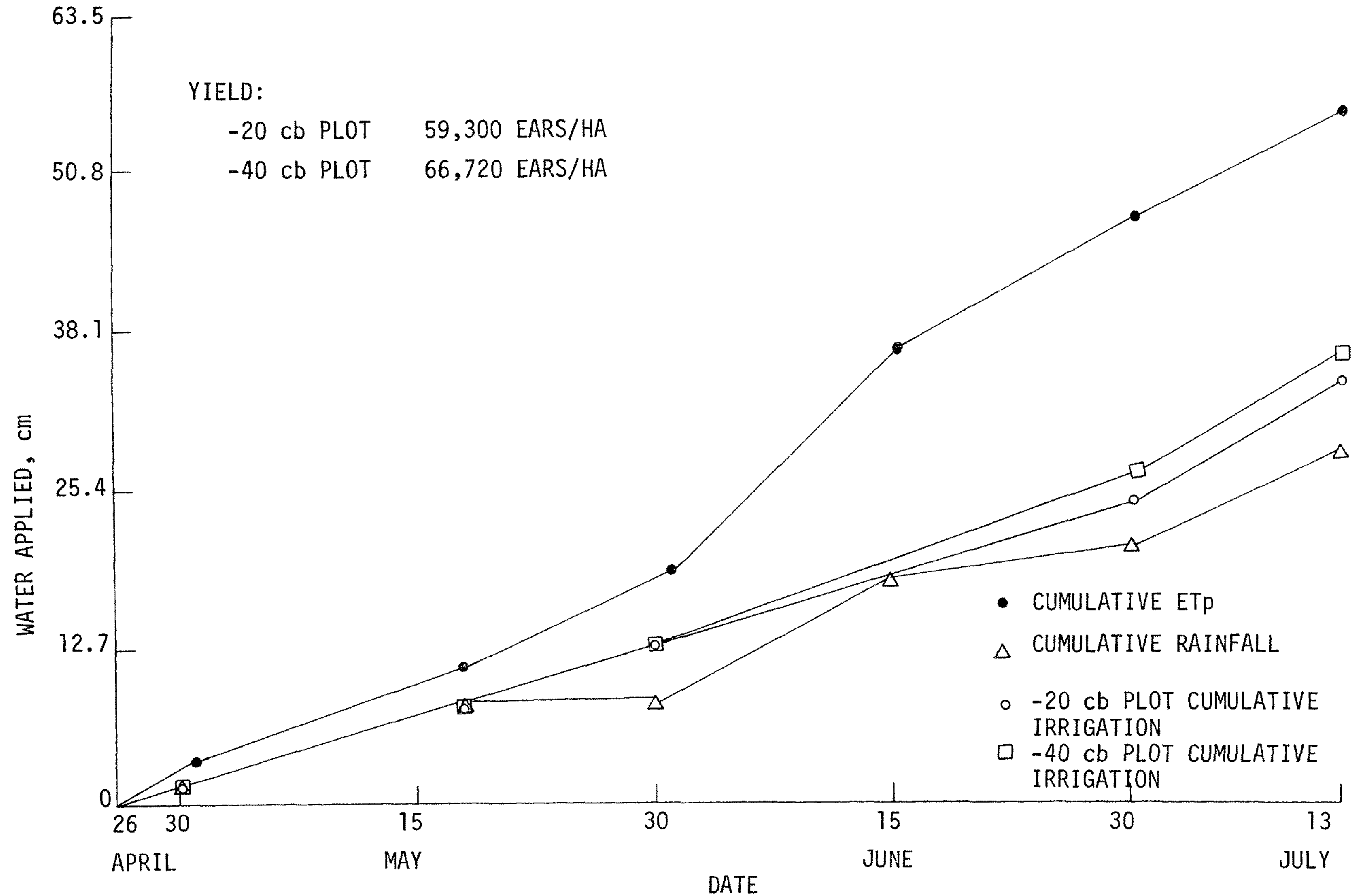


Figure 50. Cumulative amounts of applied water and potential evapotranspiration [Jensen, et al. (10)] from the automated subirrigated plots at Lubbock, Texas, during 1972.

SECTION 6

RESULTS AND DISCUSSION

OBJECTIVE 1 - CONTRIBUTION OF CURRENT IRRIGATION AND FERTILIZATION PRACTICES TO POLLUTION OF UNDERGROUND WATER

One of the objectives of this project was to determine the influence of various irrigation systems on solute movement within and below the soil profile. In this particular soil, this was a zone between the surface and the water table, approximately 9.1-m thick. Both porous bulb soil-water extracts and soil extracts were obtained. Procedures for the analyses of porous bulb soil-water and soil extracts obtained from the profile are discussed in Section 4 in chronological order. The order of discussion of the results is as follows: anions except for nitrate (nitrite, orthophosphate, chloride, sulfate), cations (sodium, calcium, magnesium, potassium, ammonium), conductivity and followed by the most important ion in the study, nitrate.

Nitrite

Analyses for nitrite from samples obtained during the first year of the study showed that 0.1 ppm or less existed in the soil; therefore, analyses were not continued.

Phosphate (Orthophosphate)

Phosphate values obtained during the course of the study are typical of those found in Figure 51. Concentrations of the extracts were generally less than 1 ppm ranging primarily from 0 to 0.3 ppm. Such concentrations of phosphate are no problem relative to the water quality of irrigation return flows. Phosphate analyses were, therefore, discontinued after the first year of the study.

Chloride

Chloride analyses from selected soil-water extracts are shown in Figures 52 through 56. Average chloride concentration of the irrigation water was 73.5 ppm as indicated by the vertical line within the graph. Chloride changes within the first year of the study on a sprinkler irrigation system are shown in Figure 52. Similar changes were found within the year in the furrow, subirrigation, and automatic subirrigation systems. Major changes in chloride concentration occurred between 0 and 1.5 m. On July 8, the concentration of chloride in this zone was low with the peak

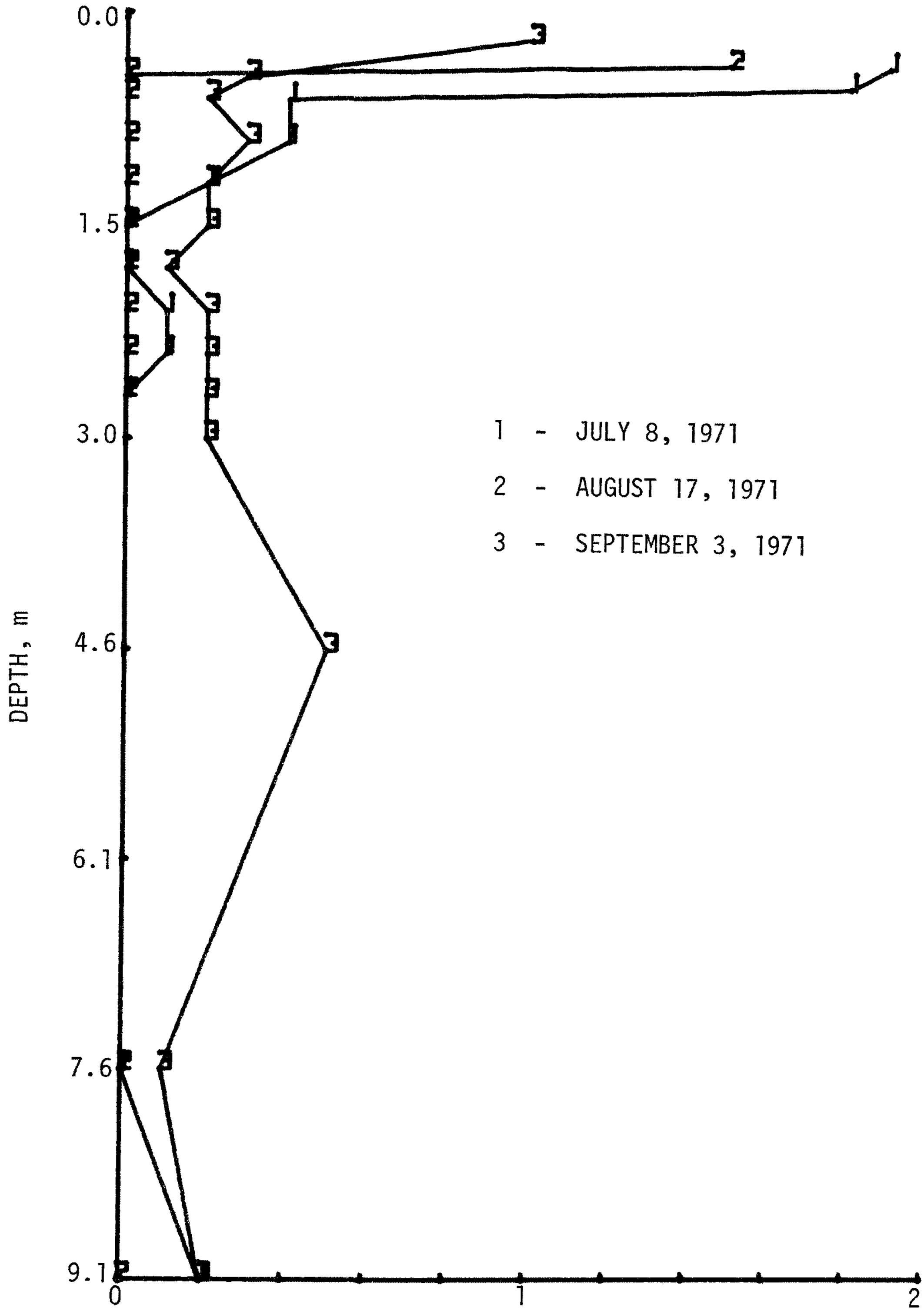


Figure 51. Phosphate concentration of porous bulb soil-water extracts from various depths during 1971 from a sprinkler irrigation system.

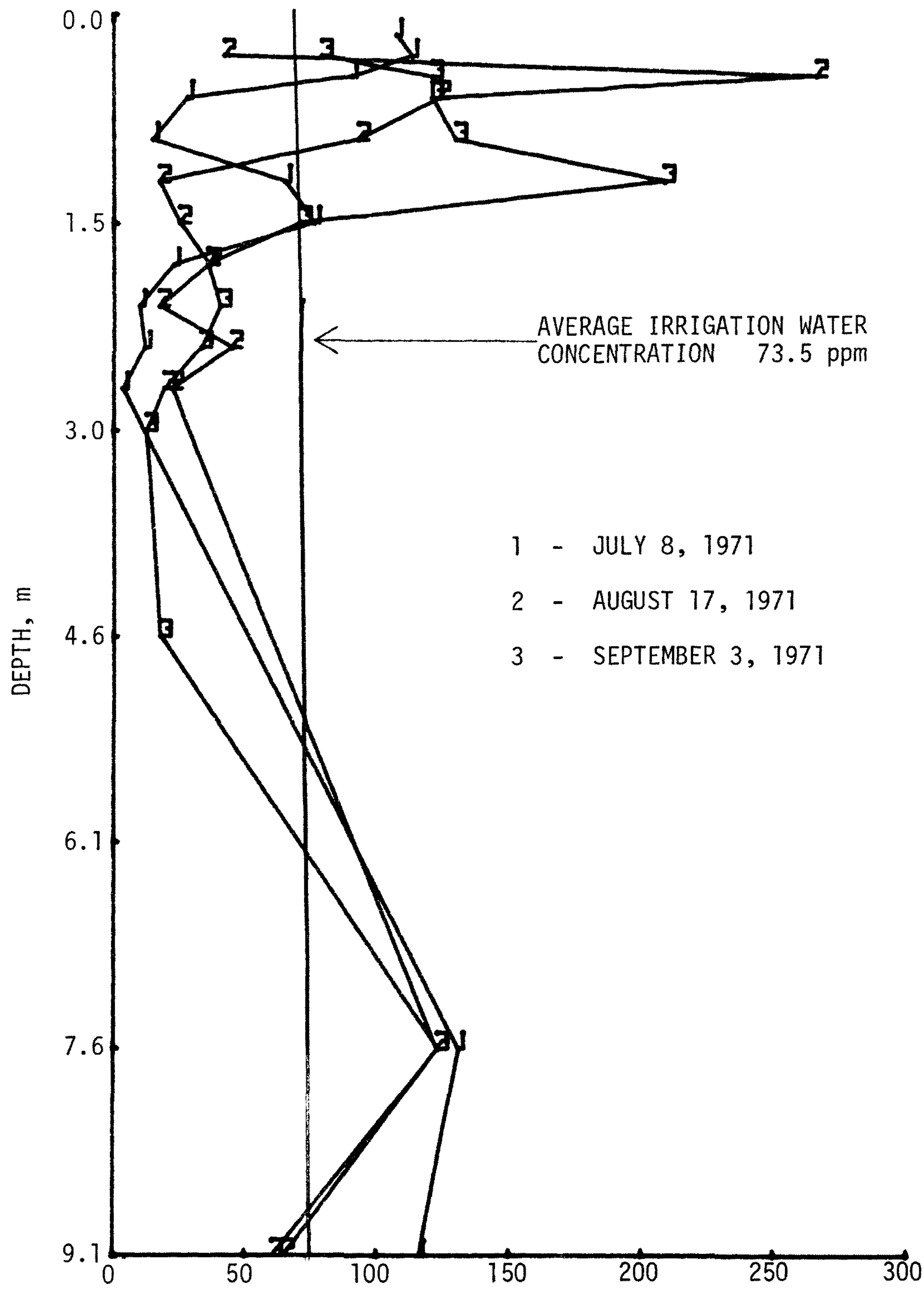


Figure 52. Chloride concentration of porous bulb soil-water extracts from various depths during 1971 from a sprinkler irrigation system.

concentration of 130 ppm occurring at 0.3 m. By August 17 the chloride concentration increased in this zone to 250 ppm at 0.9 m. Data obtained on September 3 showed a peak chloride concentration at 1.5 m. These data indicate that there was probably a concentration of chloride in the surface from evaporation. The chloride was leached due to 7.00 cm of rainfall received between July 8 and August 17 and 17.85 cm of rainfall received between August 17 and September 3. There appears to be some accumulation of chloride between 2.1 and 3.0 m between July 8 and September 3. However, the concentrations are generally less than those in the irrigation water (40.0 ppm vs 73.5 ppm). The only major change that occurred below 3.0 m was at 9.1 m where the chloride concentration decreased from 120 ppm to 60 ppm.

Changes in chloride concentrations in soil-water extracts over a two-year period (1971-1973) for the sprinkler irrigation system are given in Figure 53. There was a general increase in chloride concentration between 1971 and 1972 between 1.2 and 3.0 m to concentrations greater than those of the irrigation water. Between the 1971 and 1972 growing seasons, 32.9 cm of rainfall were received in 25 different rainfall periods. This rainfall was apparently adequate to move chloride down in the profile but not out of the profile. In 1973, the chloride concentration was much lower than in the second year of the study. This was due to rainfall received between the 1972 and 1973 growing seasons. The 70.74 cm received in 40 rainfall periods was adequate to decrease the chloride content below that of the irrigation water throughout the profile.

The same trend was followed in the furrow irrigation system between the surface and 3.0 m in that the chloride content of the extracts decreased between 1971 and 1972-73 (Figure 54) to a depth of 3.0 m. Data below 3.0 m were sketchy due to the previously mentioned problems of obtaining soil-water extracts. There was a consistent increase at 7.6 m. However, these samples were from within the water table and it is difficult to ascertain the separate contributions from the water table and leaching through the soil profile.

In the subirrigation system (Figure 55), there was a general increase in the chloride concentration immediately at the surface with a major decrease at 0.6 m where the subirrigation pipe was located. This decrease was apparent down to 1.5 m. From 1.5 to 3.0 m, there was an increase in the chloride content during 1972--but a decrease in 1973. The same trend was true from 6.1 and 7.6 m; i.e., there was an increase in the chloride concentration in the extracts during 1972 but a decrease during 1973. The decreases between 1972 and 1973 were due to the large amount of rainfall (70.74 cm) received between the two growing seasons.

In the automatic subirrigation system (Figure 56), the same trend is also true as with the manual subirrigation system. There was an increase in the surface, a general decrease down to about 2.0 m, a slight increase from 3.0 to 4.5 m and then a general decrease from 6.1 to 9.1 m between the years 1972 and 1973.

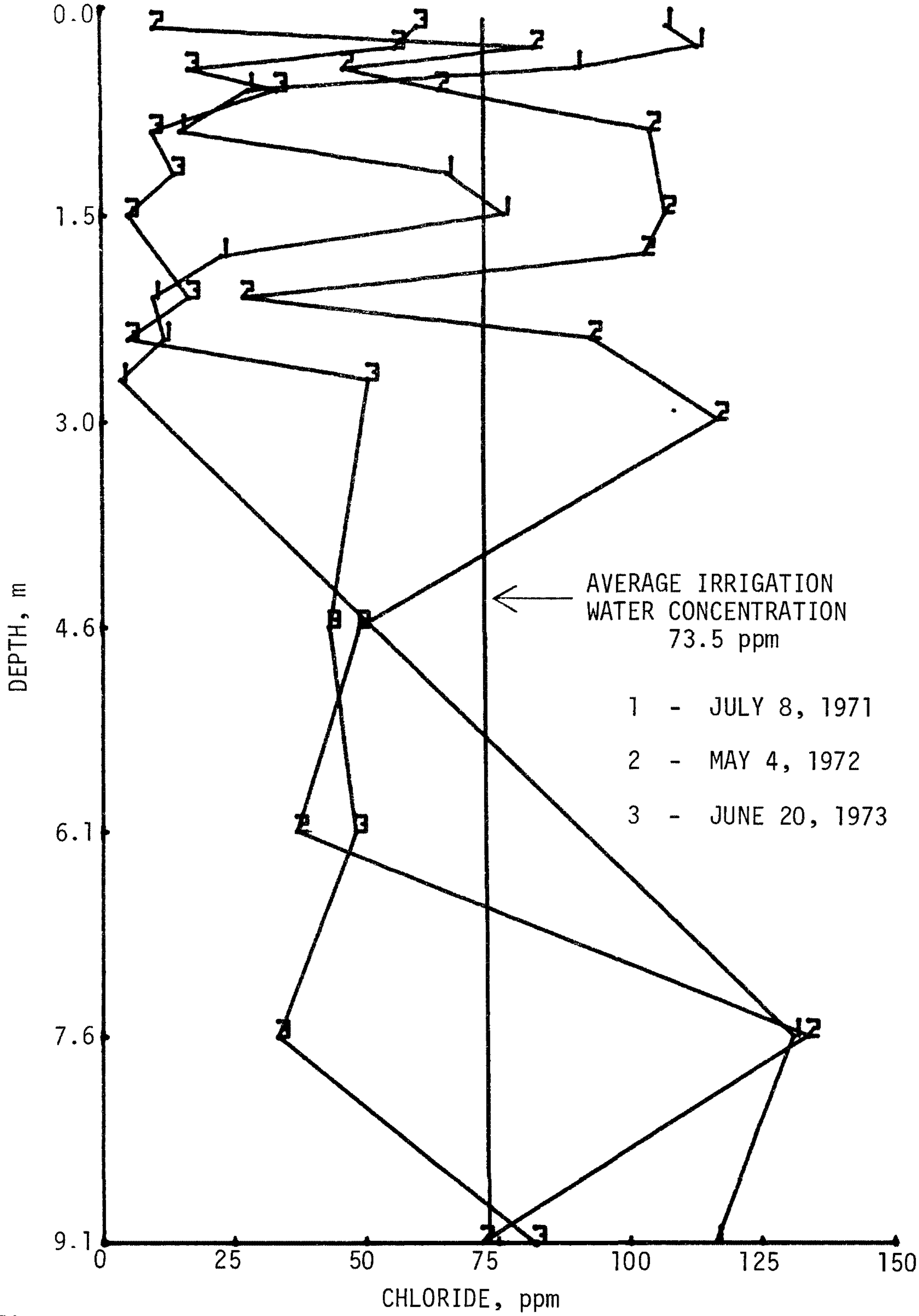


Figure 53. Chloride concentration of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a sprinkler irrigation system.

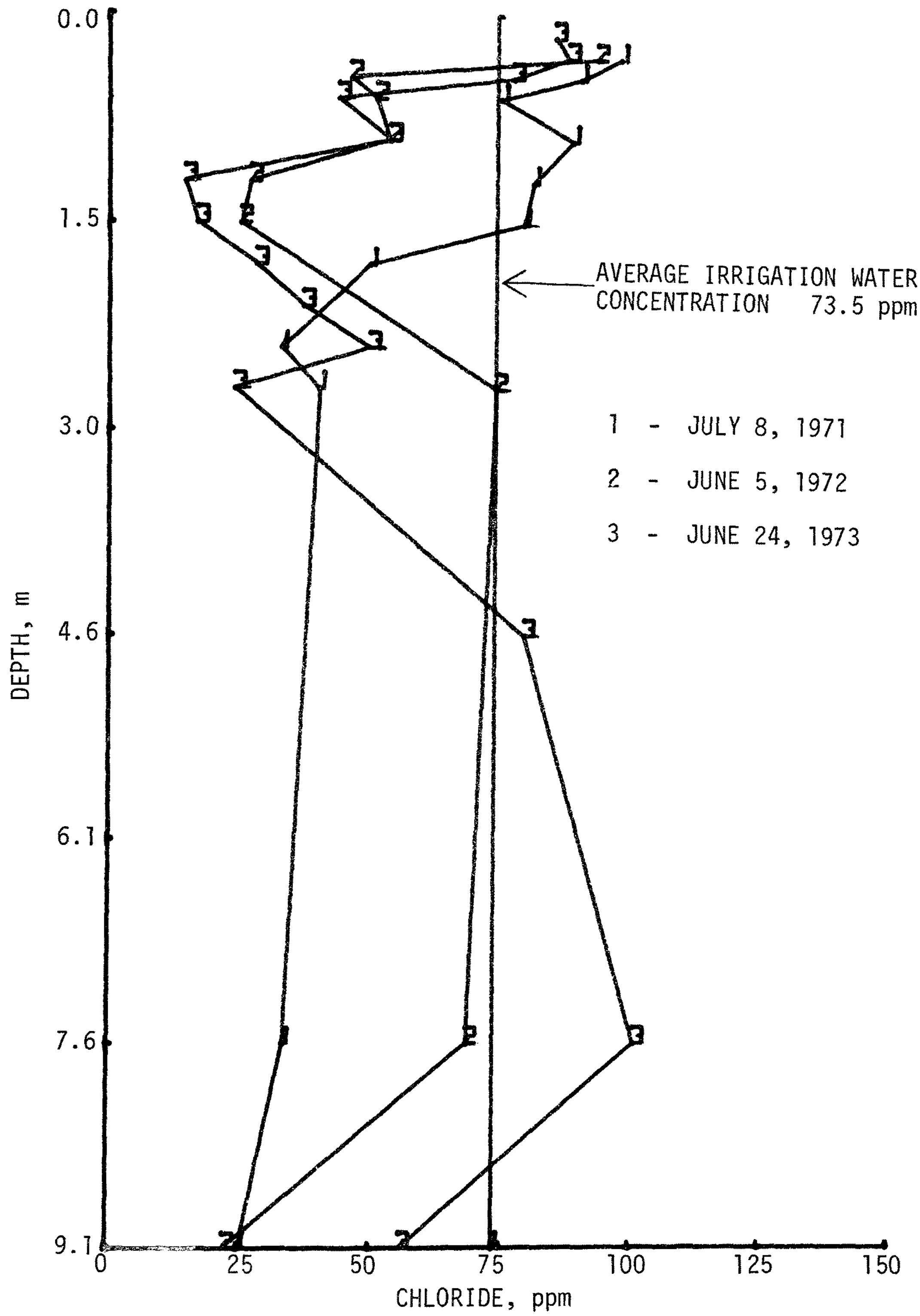


Figure 54. Chloride concentration of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a furrow irrigation system.

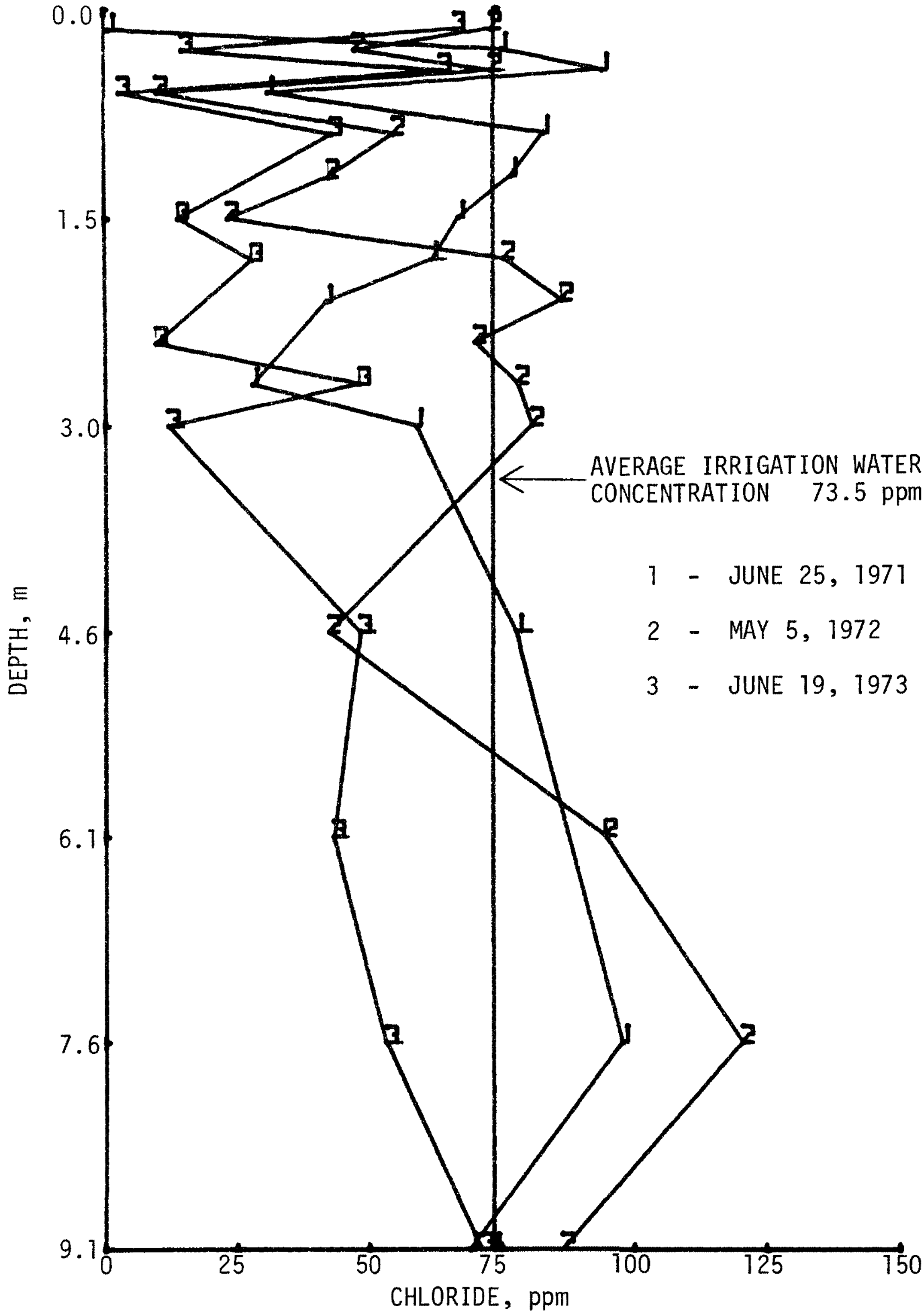


Figure 55. Chloride concentration of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a manual subirrigation system.

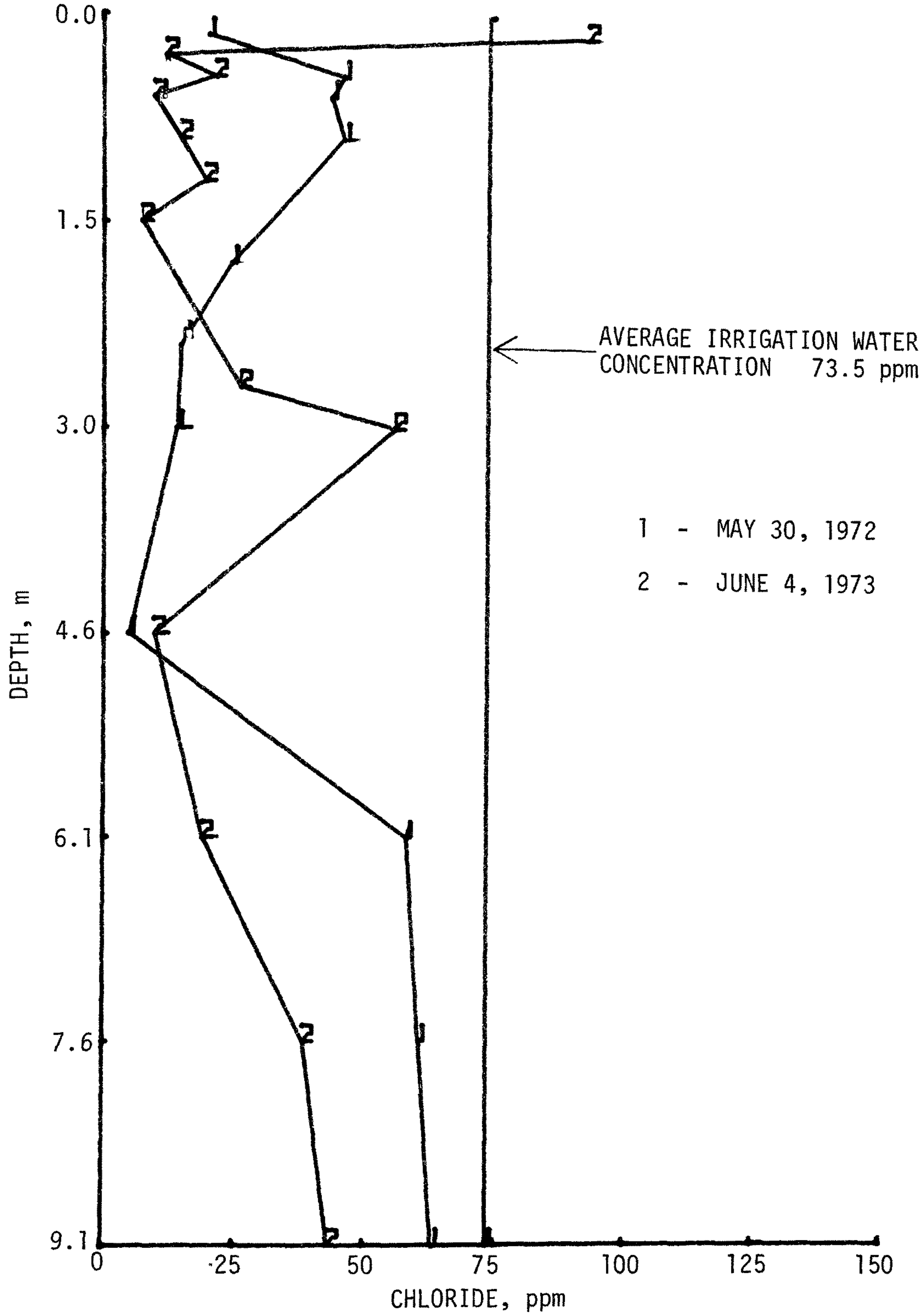


Figure 56. Chloride concentration of porous bulb soil-water extracts from various depths during 1972-1973 from an automatic subirrigation system.

In summary, there was a major decrease in the chloride content of soil-water extracts between 1971 and 1973. Rainfall received (70.74 cm) between 1972 and 1973 was apparently a major factor in improving the quality of the extracts. The ranking relative to chloride concentration was furrow irrigation > sprinkler irrigation > subirrigation > automated subirrigation. The lower chloride content of the automated subirrigation system may have been due to the fact that less chloride was added since less irrigation water was applied. No major accumulations of chloride were noted under any of the systems. Chloride concentrations were generally less than the irrigation water at the end of the three years. It was, therefore, concluded that, under the conditions of this study, chloride would not be a major pollutant of the water table.

Sulfate

Sulfate was low in samples taken on July 8, 1971 (Figure 57). It exceeded the irrigation water concentration (129 ppm) only at the surface down to 0.6 m and at 2.7 m. Between July 8 and August 17, the sulfate concentration increased to 600 ppm at 0.6 m with slight increases occurring at 0.9, 1.2, 1.5, and 1.8 m. Between August 17 and September 3, the peak at 0.6 m decreased to 300 ppm with other decreases occurring from 0.6 m down to 1.8 m. These decreases were probably due to 7.77 cm of rainfall received between August 17 and September 3. It is notable that the same conditions displaced the chloride peak from 0.6 to 1.5 m (Figure 52) but only decreased rather than displaced the sulfate peak (Figure 57).

The changes that occurred in sulfate concentrations from 1971 to 1973 in the sprinkler irrigation system are shown in Figure 58. The concentrations in the soil exceeded those of the irrigation water in 1971 in the surface 0.6, 3.0, and 9.1 m. During 1972 and 1973, the concentrations in the surface 0.6 m fluctuated but were lower than the irrigation water and values obtained in 1971. There was an increase in sulfate concentration between 1.5 and 2.7 m compared to the values obtained during 1971. Between 3.0 and 9.1 m the sulfate concentrations were generally lower in 1972 and 1973 than they were in 1971. The exception to this was at 7.6 m where the sulfate concentration was higher in 1973 than in 1971 and 1972. At the end of the three-year period, the soil-water extracts exceeded the concentrations of the irrigation water concentration only at 2.4, 2.7, and 9.1 m. In general, the quality of irrigation return flows was better in 1973 than 1971 in the sprinkler-irrigated plots.

Sulfate concentrations of soil-water extracts from the furrow irrigation system are shown in Figure 59. The data show a definite movement of sulfate peaks within the surface 3.0 m between years. The peak at 0.3 to 0.6 m present in 1971 moved to 1.2 m in 1972 and to 2.7 m in 1973. Another peak was initiated in 1972 and 1973 at 0.3 m, probably from evaporation of irrigation water. The location of the peak at 2.7 m in the furrow-irrigated plot was in the same location as one in the sprinkler-irrigated plot (Figure 58). There was little change in the sulfate concentrations below 3.0 m in the furrow irrigation system.

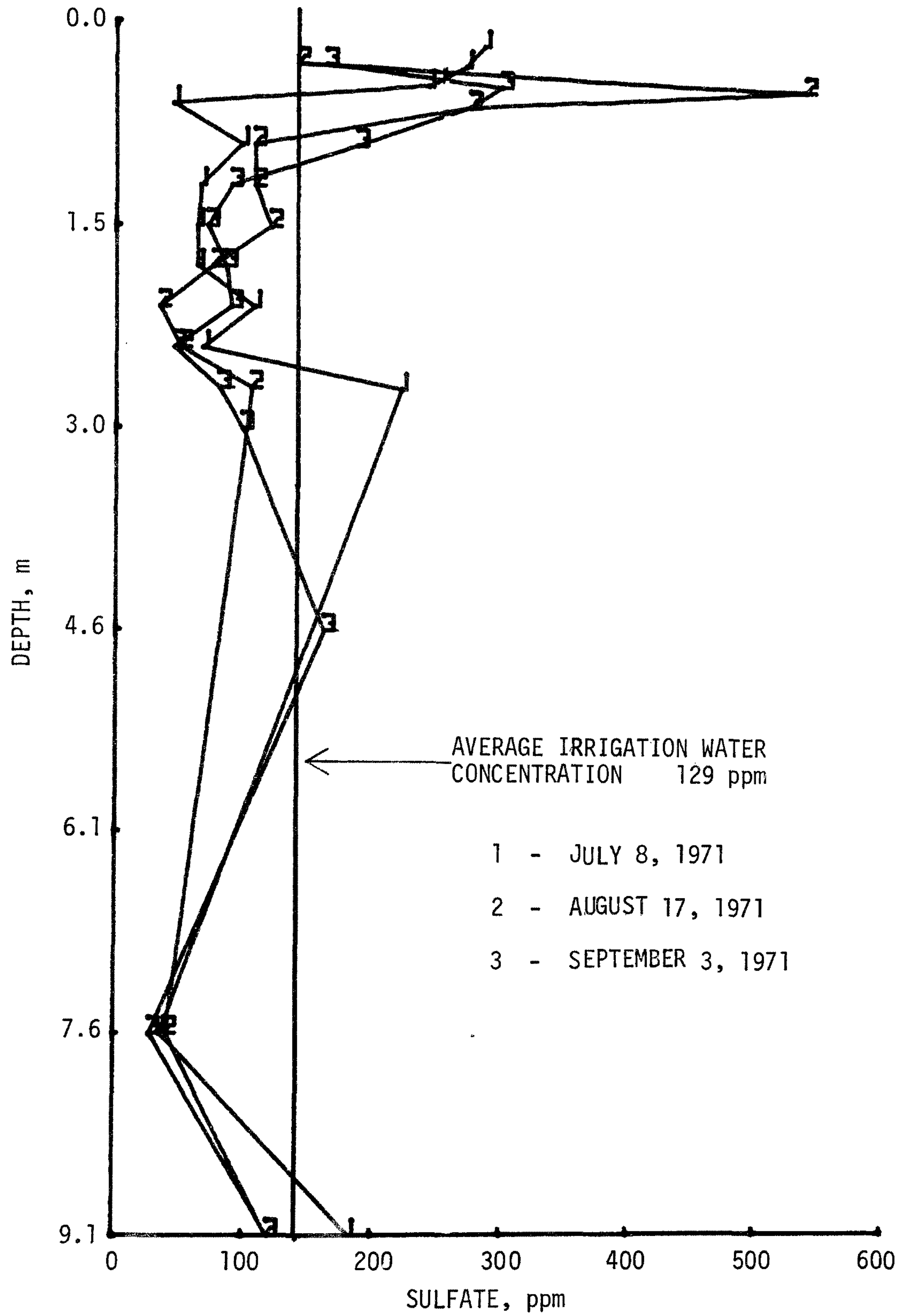


Figure 57. Sulfate concentration of porous bulb soil-water extracts from various depths during 1971 from a sprinkler irrigation system.

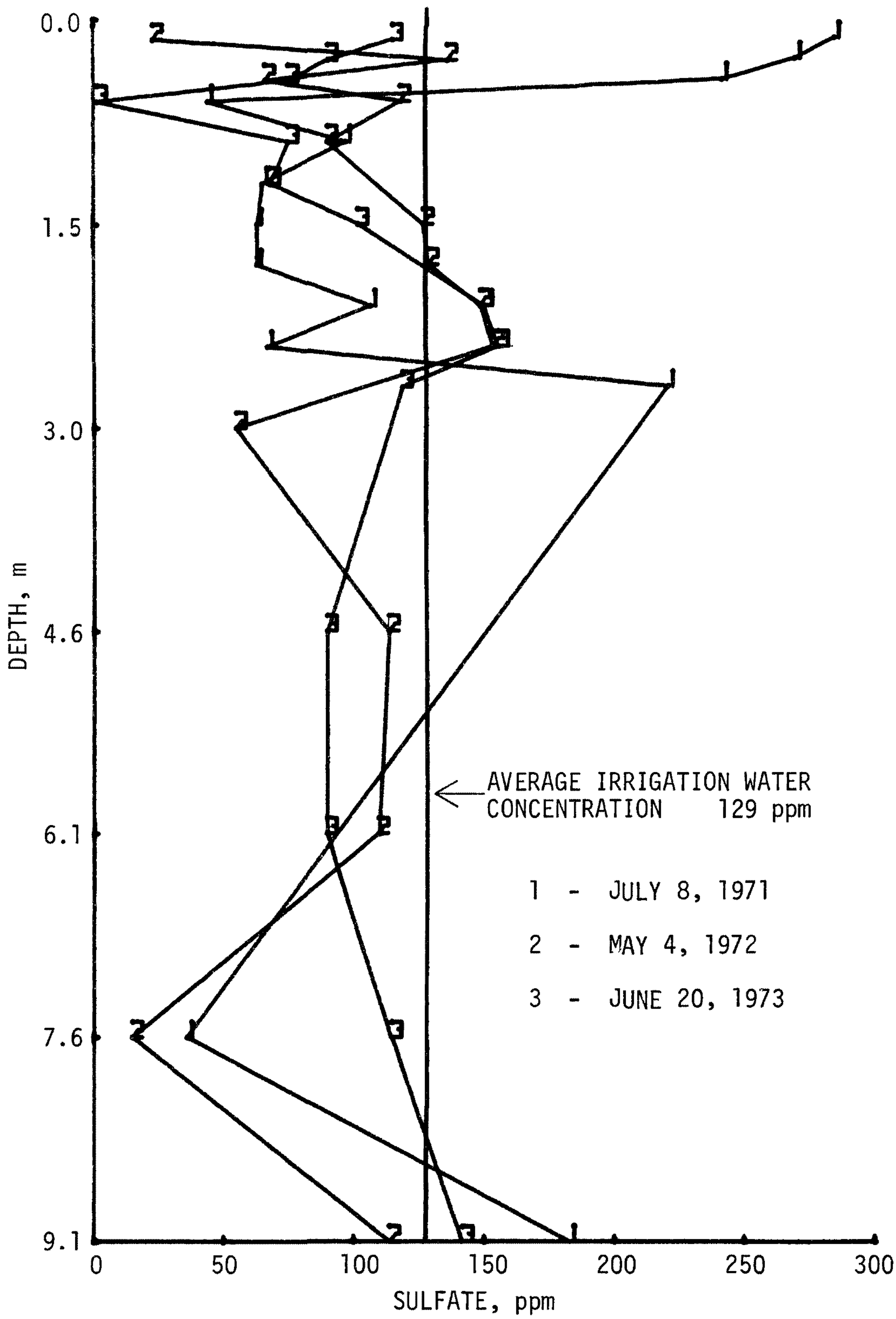


Figure 58. Sulfate concentration of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a sprinkler irrigation system.

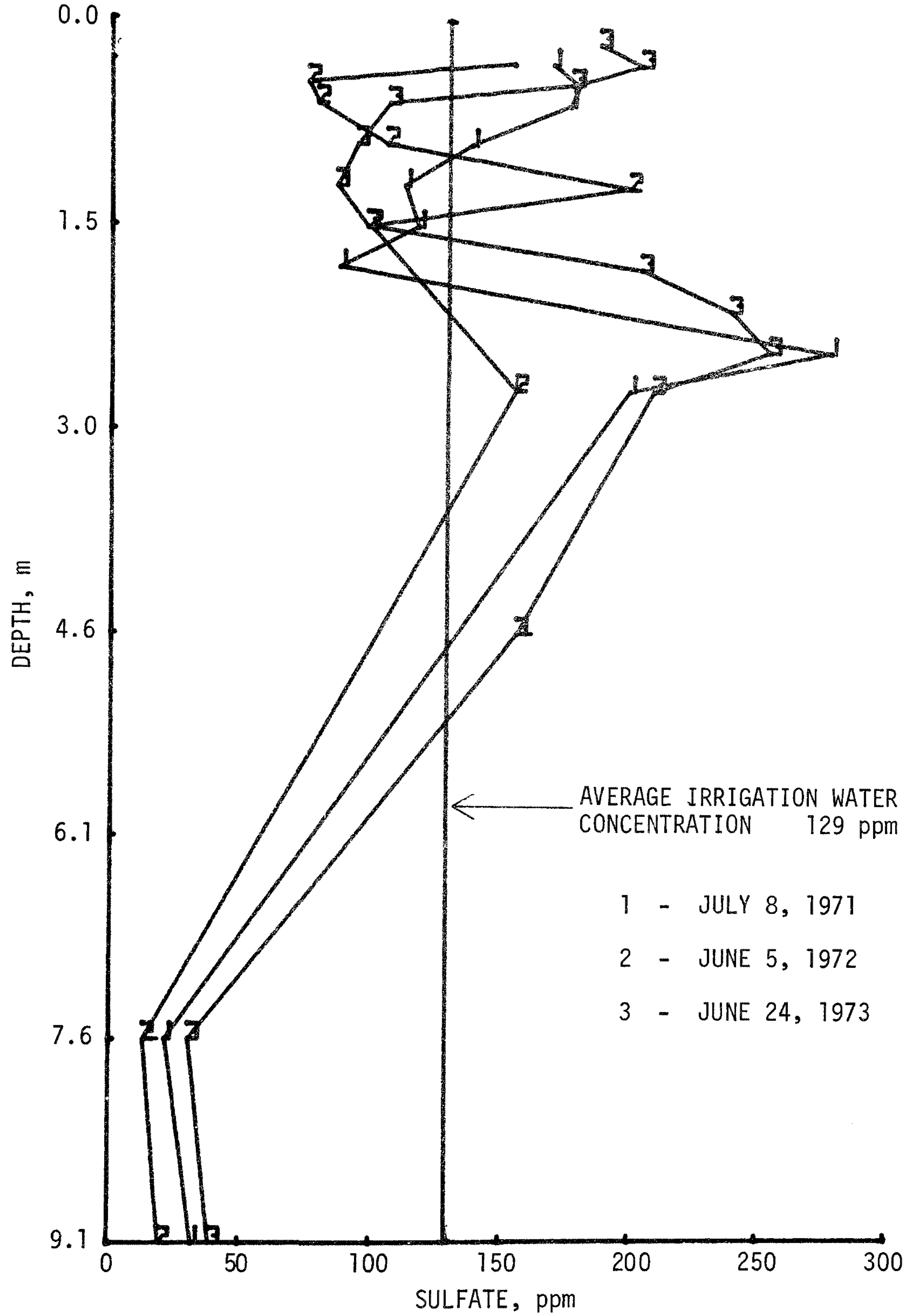


Figure 59. Sulfate concentration of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a furrow irrigation system.

Soil-water extract sulfate concentrations for a subirrigation system are given in Figure 60. As with chloride, there was a constant decrease in the sulfate concentration between 1971 and 1973 at 0.6 to 0.9 m due to the location of the subirrigation pipe. In 1972, there was an accumulation of sulfate at 1.5 m which moved to 2.7 to 3.3 m in 1973. This is the same zone of increase in the sprinkler (Figure 58) and furrow (Figure 59) irrigation systems. Below 3.0 m there was an increase in sulfate at 6.0 m, with little change occurring at 4.6, 7.6, and 9.1 m between 1971 and 1973. At the end of the three-year period, the sulfate concentration exceeded that of the irrigation water only at 0.15, 0.3, 2.7, and 3.0 m, indicating that the quality of the irrigation return flows relative to sulfate was high.

The automated subirrigation system (Figure 61) had by far the lowest sulfate concentrations in the profile. There was an increase at the surface as was the case with chloride. There were decreases in sulfate concentration at 0.3 to 0.6 m, slight increases from 1.5 to 3.0 m, with little change in concentration occurring below 3.0 m.

In summary, the data indicate that water flow from subirrigation systems decreased the sulfate concentration at 0.6 to 0.9 m. An accumulation of sulfate was indicated in all three manually-operated systems at 2.7 to 3.0 m (Figures 58 through 60). Peaks of sulfate concentration remained static while the chloride peaks tended to move in the profile. In 1973, the overall ranking of the sulfate concentration of the soil-water extracts from the various irrigation systems was furrow irrigation > sprinkler irrigation ≅ subirrigation > automatic subirrigation. Below 4.6 m the sulfate concentrations of the extracts were lower than that of the irrigation water indicating the quality of the leachate reaching the water table was high from all systems. It was therefore concluded from this study that sulfate was not a pollution hazard.

Sodium

Changes in sodium concentration obtained during the three years of the study are shown in Figures 62 through 66. During the growing season most of the changes in the sprinkler irrigation system (Figure 62) occurred above 1.5 m and below 4.6 m. Between 0 and 0.6 m there was a general tendency for the peak concentration to move down in the soil profile as the season progressed. An accumulation of sodium was indicated at 1.5 m. Below 4.6 m there was a decrease in the sodium concentration. There was no significant relationship between the sodium concentration and the sulfate (Figure 57) and chloride concentration (Figure 52) between the various dates during the growing season.

There was a general increase in sodium concentration between 1971 and 1973 between 0 and 3.0 m in the sprinkler irrigation system (Figure 63) except at 1.2 and 1.5 m. Below 3.0 m there was a decrease in the sodium concentration of the soil-water extracts between 1971 and 1973. Only at 0.15 and 0.6 m did the concentration exceed the concentration of the irrigation water at the end of the three years.

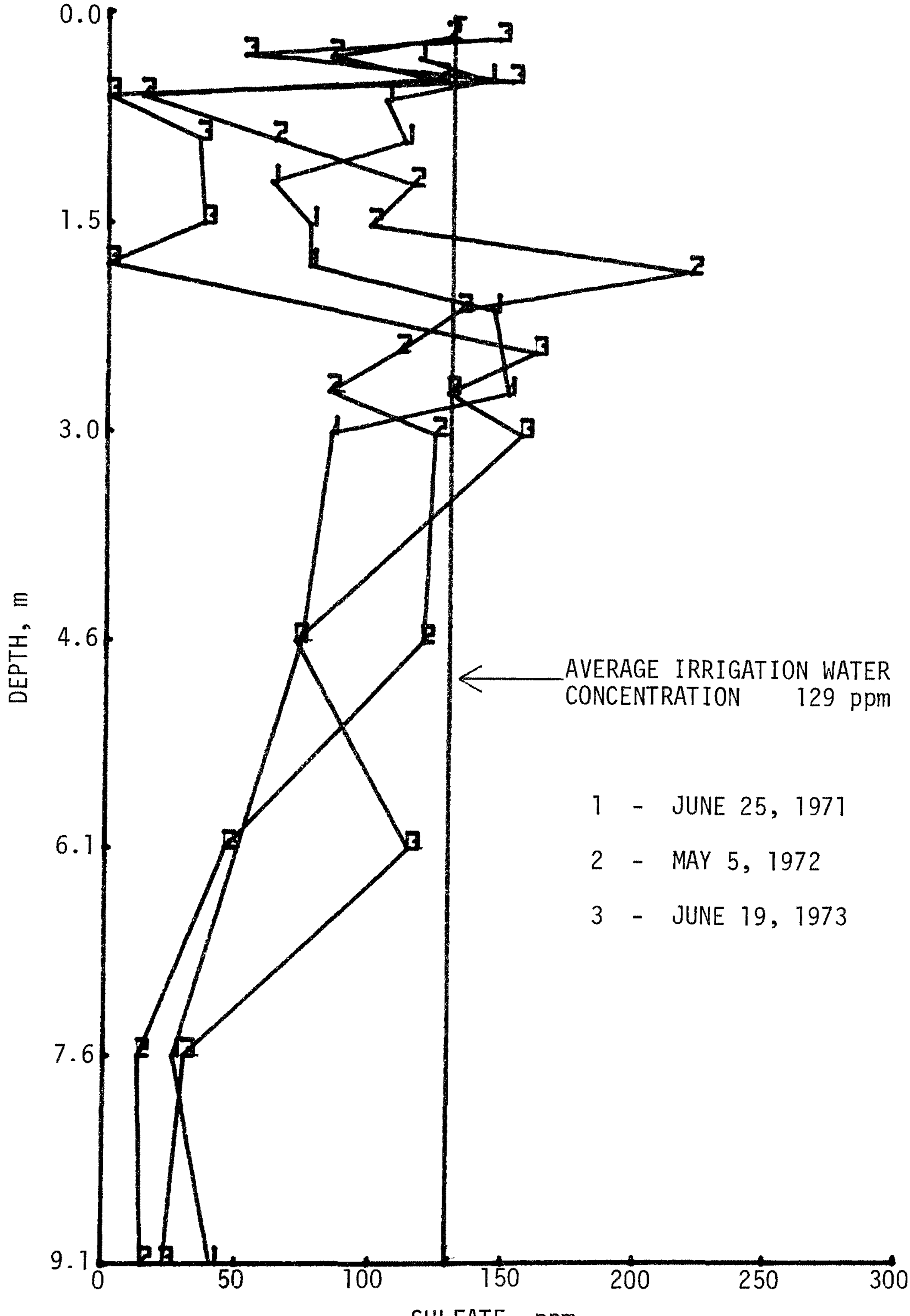


Figure 60. Sulfate concentration of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a manual subirrigation system.

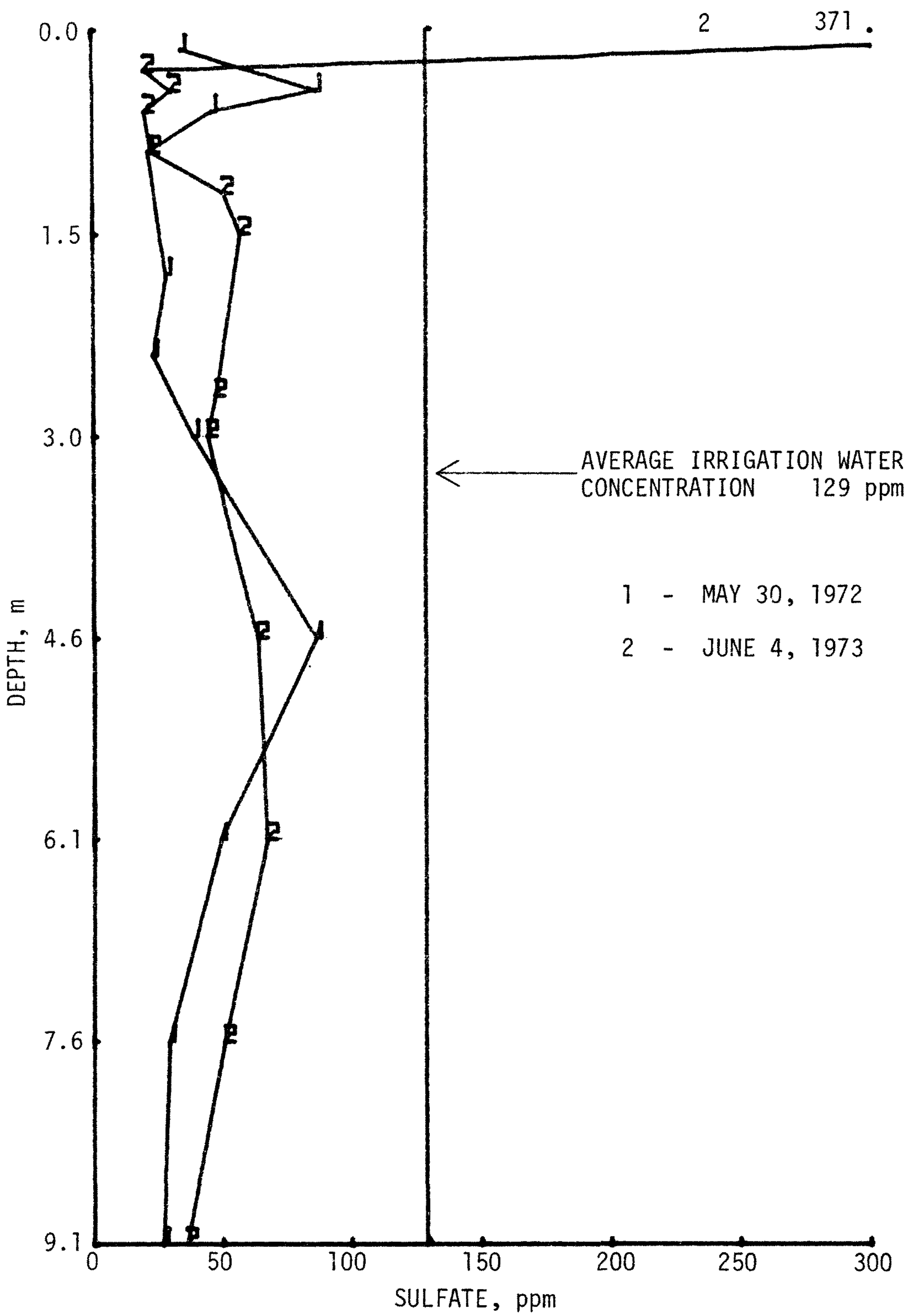


Figure 61. Sulfate concentration of porous bulb soil-water extracts from various depths during 1972-1973 from an automatic subirrigation system.

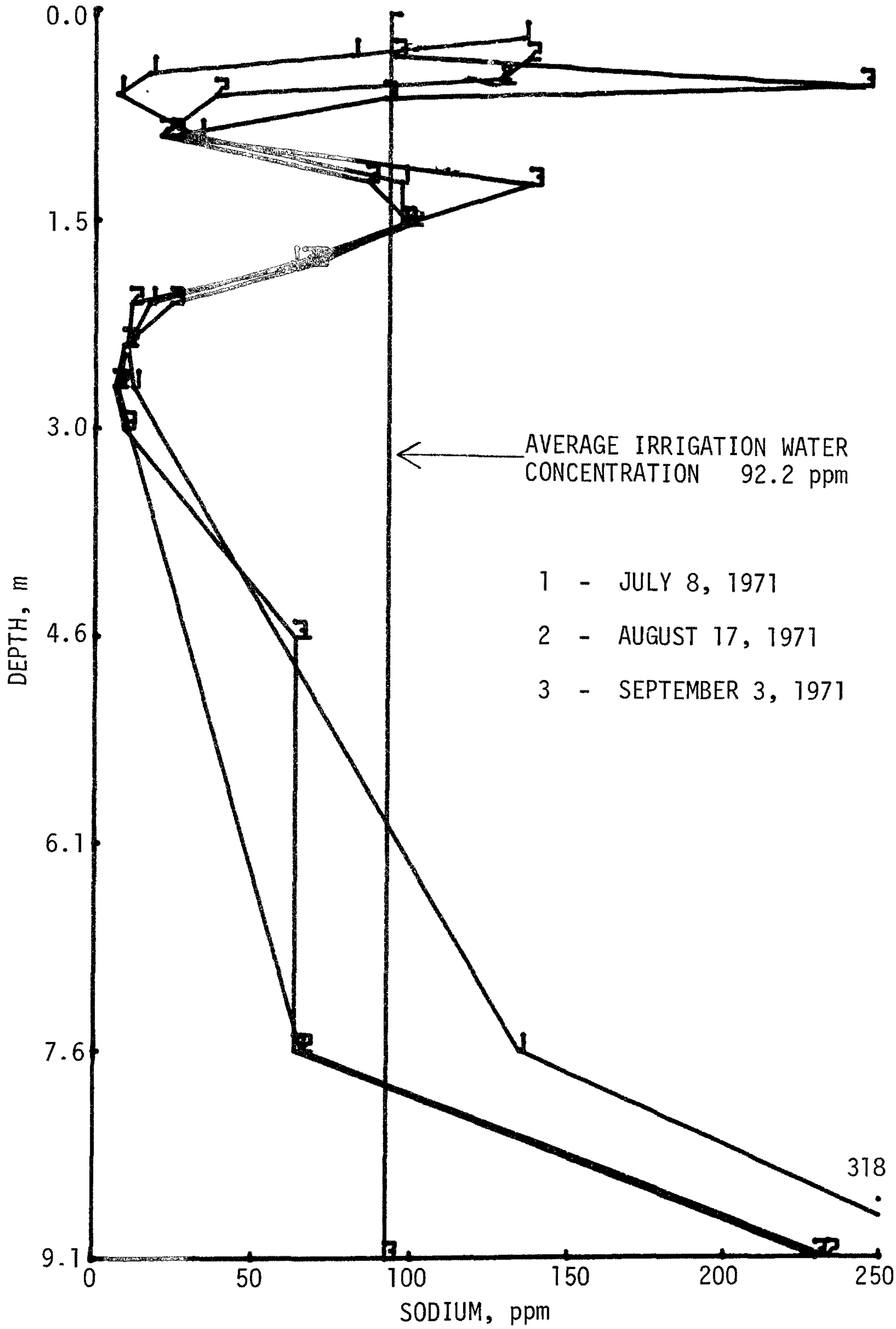


Figure 62. Sodium concentration of porous bulb soil-water extracts from various depths during 1971 from a sprinkler irrigation system.

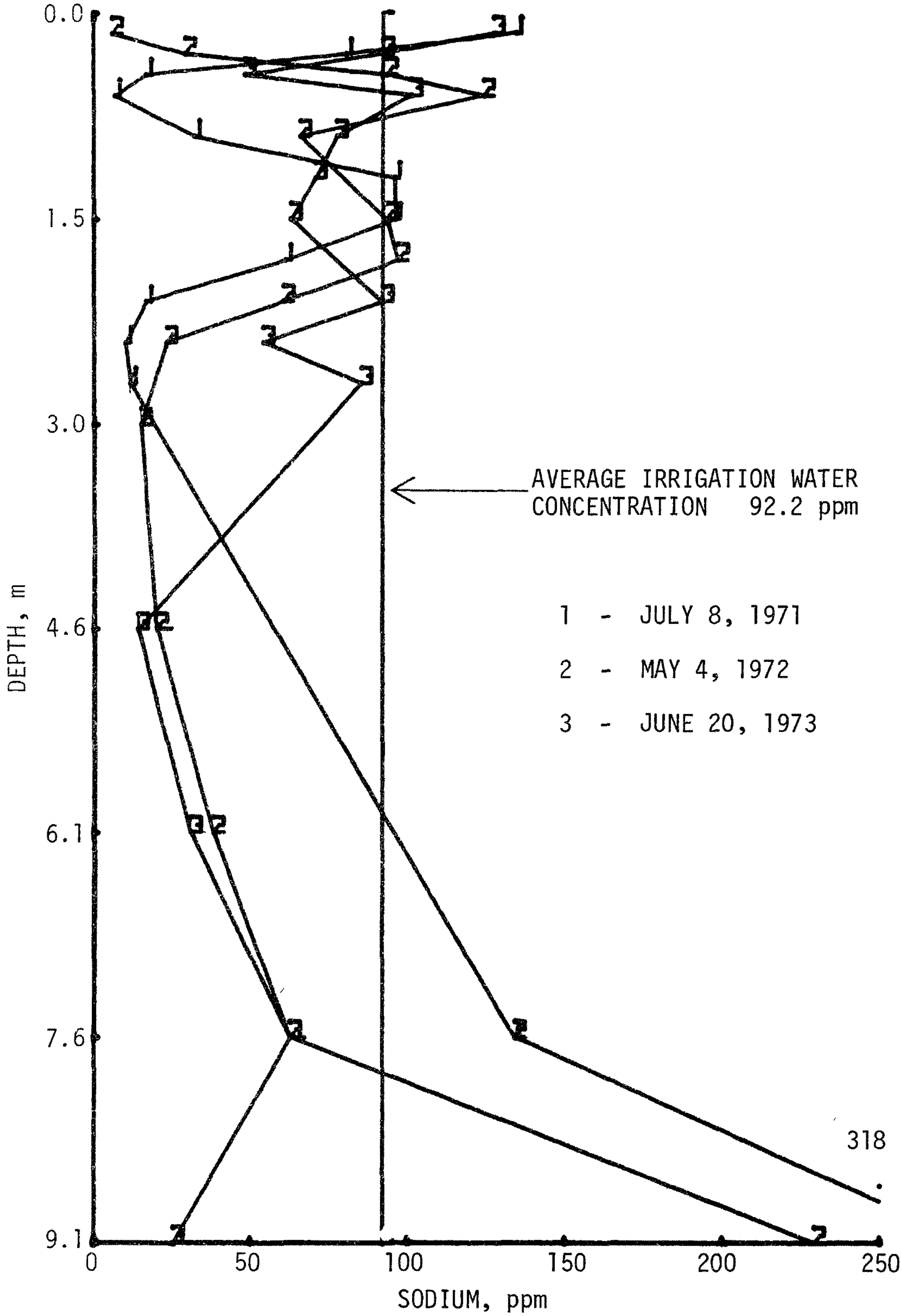


Figure 63. Sodium concentration of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a sprinkler irrigation system.

The concentration of sodium in the furrow irrigation system (Figure 64) was generally higher than the concentration of the sprinkler irrigation system (Figure 63) at the end of the three-year period. There was a development of a sodium peak at 0.3 m under the furrow irrigation system (Figure 64) between 1971 and 1973 due to evaporation. A peak located at 0.9 m in 1971 moved to 1.2 m in 1972 and 1.5 to 1.8 m in 1973. No significant change occurred in the sodium concentration below 3.0 m during the three years of the study.

Decreases and increases in the manual subirrigation system (Figure 65) were noted in sodium concentration during the three-year period. Decreases were noted between 0.3 and 0.6 m where the subirrigation pipe was located. These ions were apparently moved to the surface and to a zone between 0.9 and 3.0 m. The decrease noted at 0.3 and 0.6 m is similar to that noted with chloride (Figure 55) and sulfate (Figure 60). Below 3.0 m there was a decrease in the sodium concentration of the soil-water extracts during the three-year period.

A zone of low sodium concentration was also noted in the automated subirrigation system (Figure 66) at 0.3 to 0.6 m where the subirrigation pipe was located. It is difficult to comment on the samples between 1.5 and 3.0 m since the samples were obtained from different depths on the two dates. Sampling was a problem in this zone with the automated subirrigation system due to small amounts of irrigation water added which did not percolate into this zone. Below 3.0 m there was no change in sodium concentration.

In summary, there were no deleterious accumulations of sodium in the soil profile during the three years of the study. At the end of the three-year period, the sodium concentration of extracts below 3.0 m from sprinkler, subirrigation, and automated subirrigation systems was less than that of the irrigation water. Only at 7.5 and 9.0 m was the concentration of sodium from the furrow irrigation system higher than the irrigation water, and these concentrations did not change during the three years for which soil-water extracts were obtained. Above 3.0 m the sodium concentration from the different systems was greatest in the manual subirrigation system followed by the furrow, sprinkler, and automatic subirrigation systems. The subirrigation systems had low concentrations of sodium at 0.3 to 0.6 m where the subirrigation pipe was located.

Calcium

Calcium data obtained are shown in Figures 67 through 71. During 1971 an overall increase in the calcium concentration of the extracts was indicated at 0.6 m and from 1.8 to 9.1 m in the sprinkler irrigation system (Figure 67). The movement of a peak was indicated from 1.8 to 2.4 to 2.7 m between July 8, August 17, and September 3, respectively. However, the overall increases noted during 1971 below 3.0 m were not noted over the three years of the study (Figure 68). There was a major increase between 1971 and 1972 at 0.9 m. This peak remained stable and became broader between 1972 and 1973.

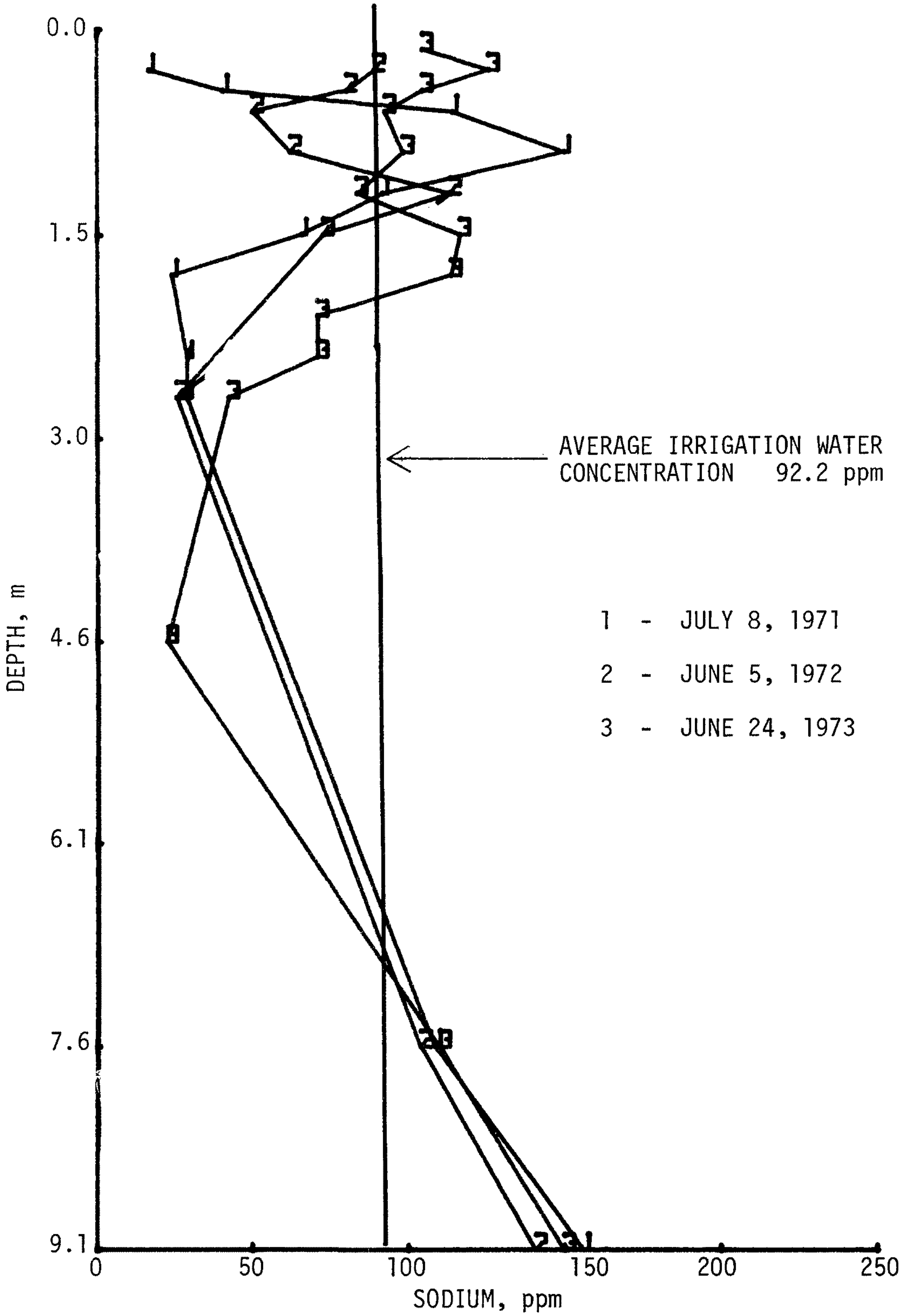


Figure 64. Sodium concentration of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a furrow irrigation system.

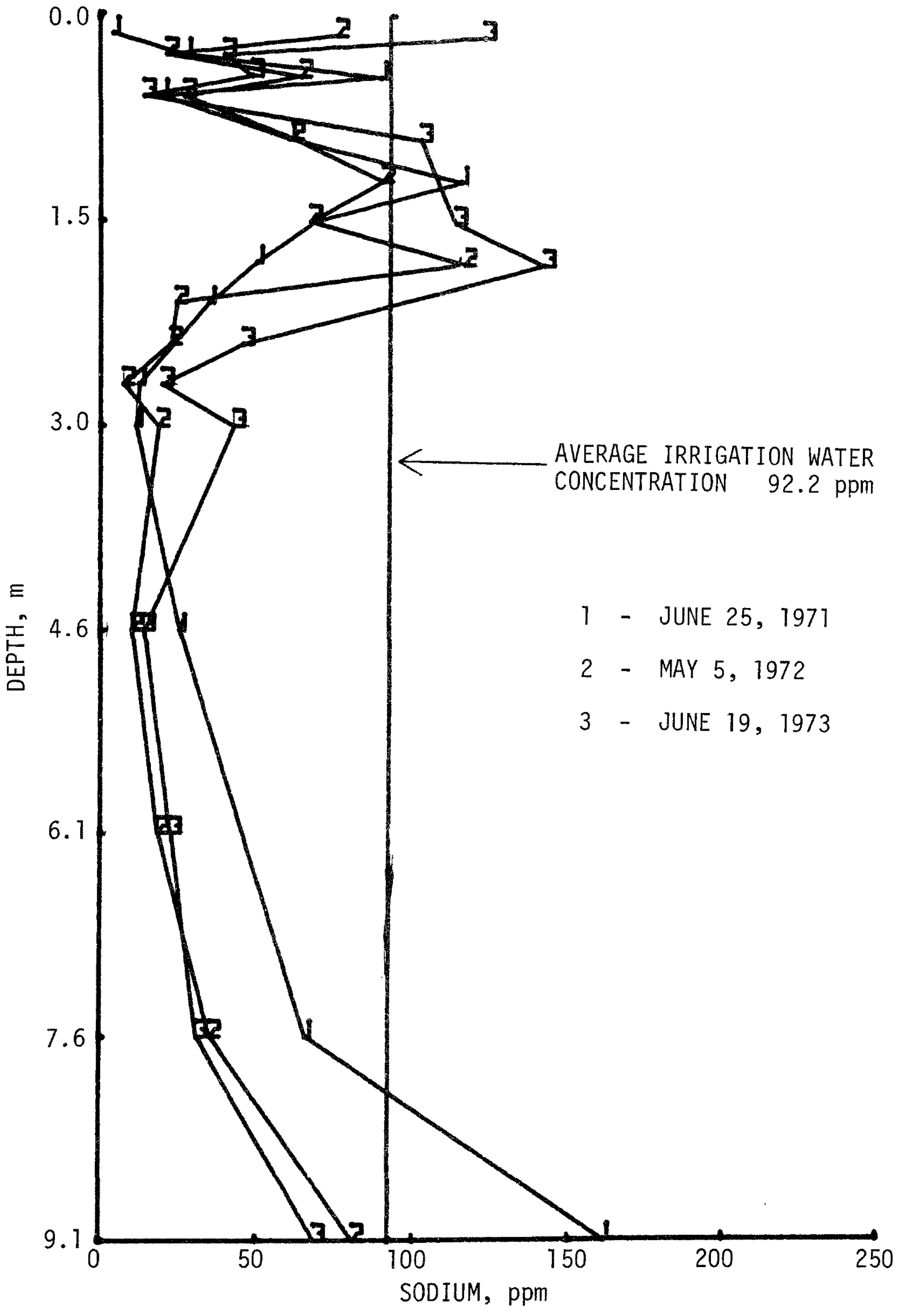


Figure 65. Sodium concentration of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a manual subirrigation system.

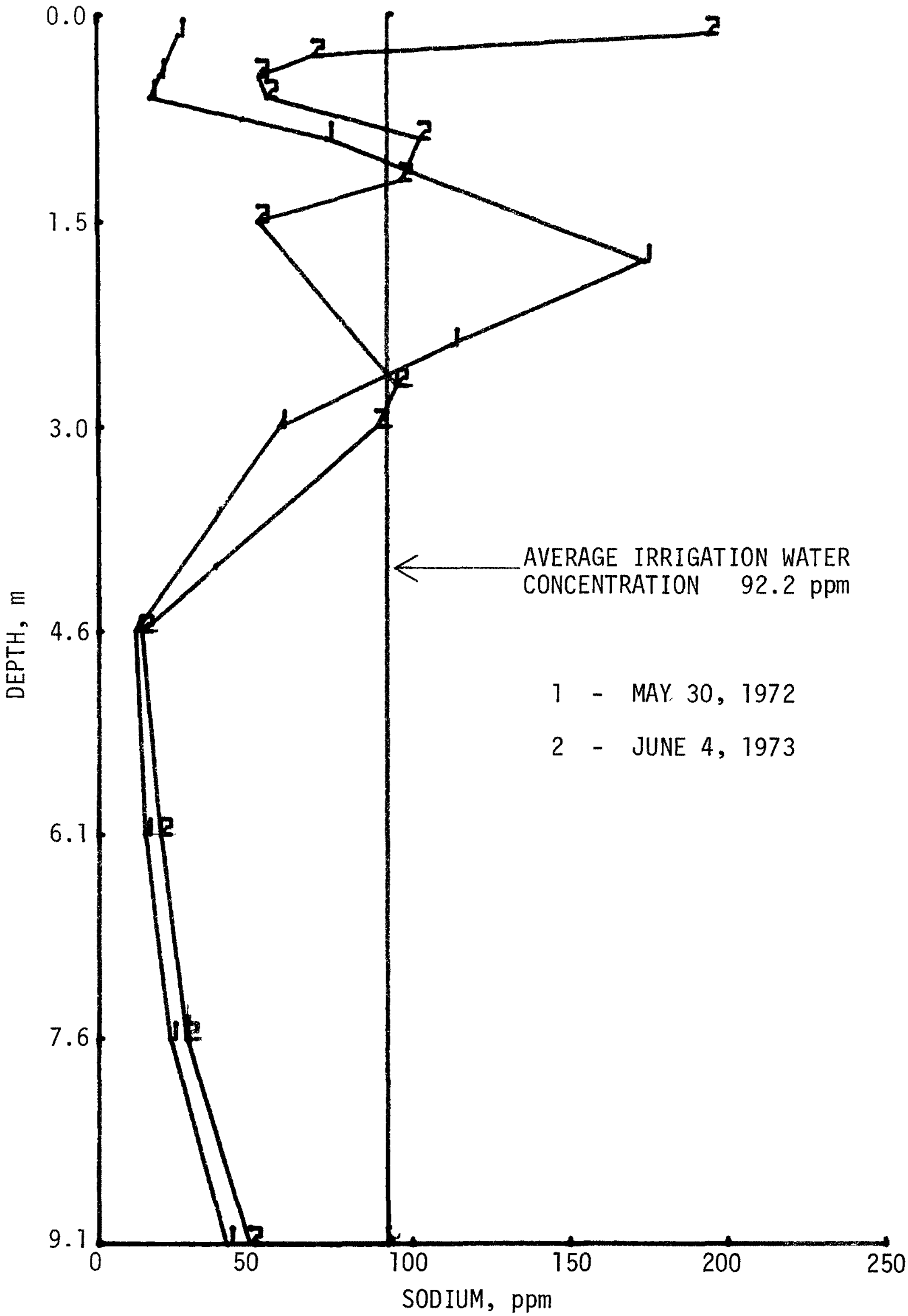


Figure 66. Sodium concentration of porous bulb soil-water extracts from various depths during 1972-1973 from an automatic subirrigation system.

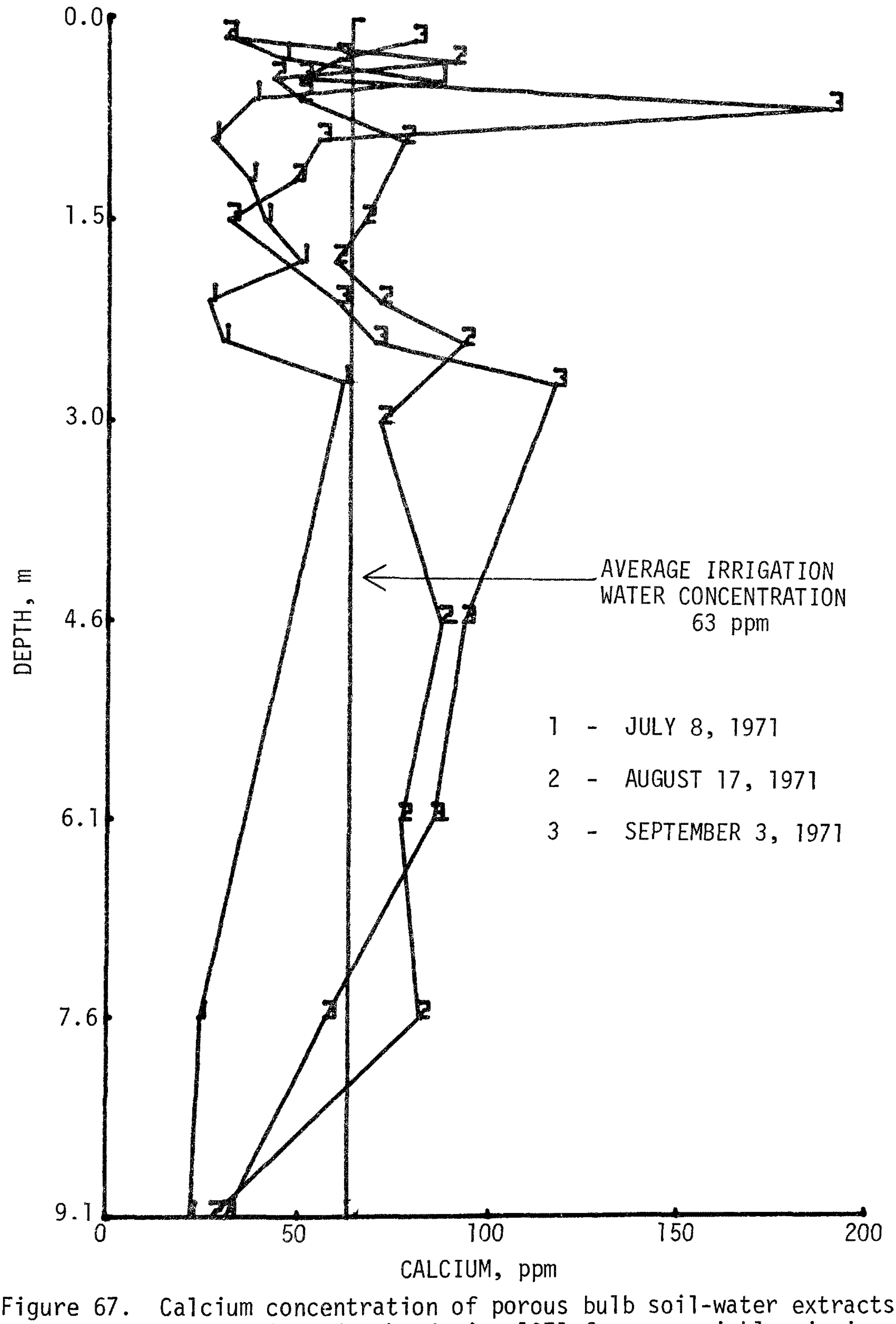


Figure 67. Calcium concentration of porous bulb soil-water extracts from various depths during 1971 from a sprinkler irrigation system.

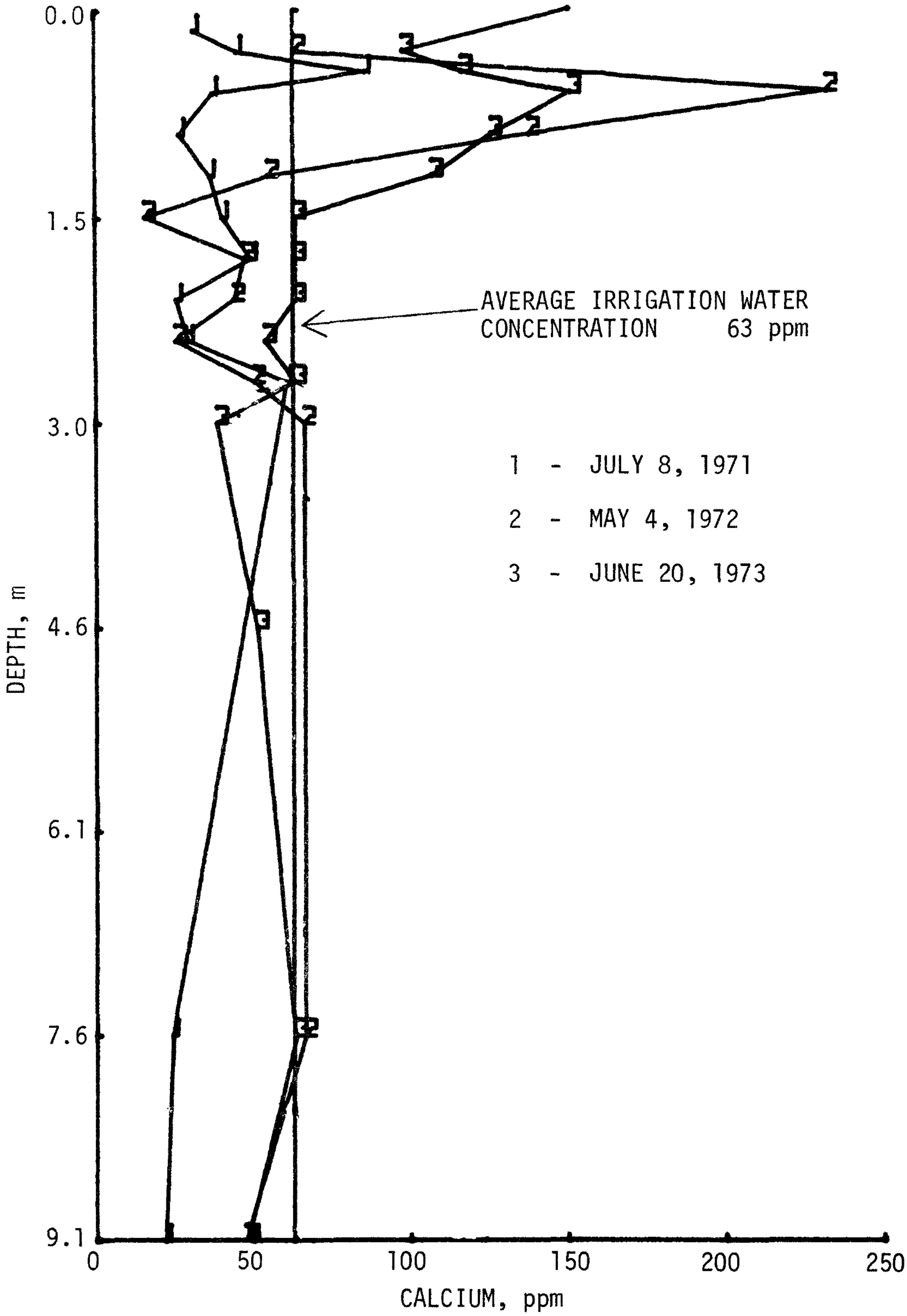


Figure 68. Calcium concentration of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a sprinkler irrigation system.

The primary changes in the furrow irrigation system (Figure 69) occurred between 1971 and the last two years of the study. Increases in the calcium concentration of the extracts from 1971 to 1972 between 0.6 and 1.2 m and 1.8 to 9.1 m remained stable through 1973. The rains received between 1972 and 1973 apparently did not affect the calcium concentrations as they did the chloride concentrations (Figure 54).

Decreases in the calcium concentration in the 0.15-to 0.9-m zone in the manual subirrigation system (Figure 70) were similar to those of other ions (Figures 55, 60, and 65). A major increase in calcium concentration to 170 ppm at 2.1 m was noted in 1972. However, in 1973 the calcium concentration of the extracts was approximately equal to that of the irrigation water (63 ppm).

The automated subirrigation system (Figure 71) had a low calcium concentration in the zone of influence of the subirrigation pipe (0.3 to 0.6 m). Increases in calcium concentration were noted at 0.15 and 0.9 m indicating the subirrigation system had moved the calcium to the periphery of its application zone. Calcium concentrations of extracts below 1.5 m were lower in 1973 than in 1972.

In summary, the overall quality of the irrigation return flow with respect to calcium at the end of the three-year period was high. The order of calcium concentrations at the end of the three-year period with respect to irrigation systems was furrow > sprinkler > subirrigation > automatic subirrigation. The sprinkler irrigation system had the highest concentrations above 1.5 m while the furrow irrigation system had the highest concentration below 1.5 m. At the end of the three-year period, the calcium concentration of the extracts was approximately equal to that of irrigation water in the manually-subirrigated plots and less than irrigation water in the automatically-subirrigated plots. Since less water was applied through the automated subirrigation systems, it appears that the amount of water applied as well as the irrigation system may influence the ion concentration in the profiles below irrigations systems.

Magnesium

Data on magnesium concentration of soil-water extracts from the various irrigation systems are shown in Figures 72 through 75. These data were obtained only during the 1972 and 1973 crop years. In the sprinkler irrigation system (Figure 72), there was some increase in concentration in the surface at the 0.3 and 0.9 m depths as well as the 2.7 and 6.1 m depths. Otherwise, there was a general decrease in the magnesium concentration between the two years. Concentrations of the extracts exceeded those of the irrigation water (43.3 ppm) only below 2.7 m, and these values decreased during the two years.

Concentrations of magnesium in the surface 1.5 m were lower in the furrow irrigation system (Figure 73) than the sprinkler irrigation system (Figure 72). Increases in magnesium occurred between the surface and 1.2 m at 1.5, 1.8, and 2.1 m and 4.6 m down to 9.1 m in the furrow irrigation system. There was a general overall increase between 1972 and 1973, but

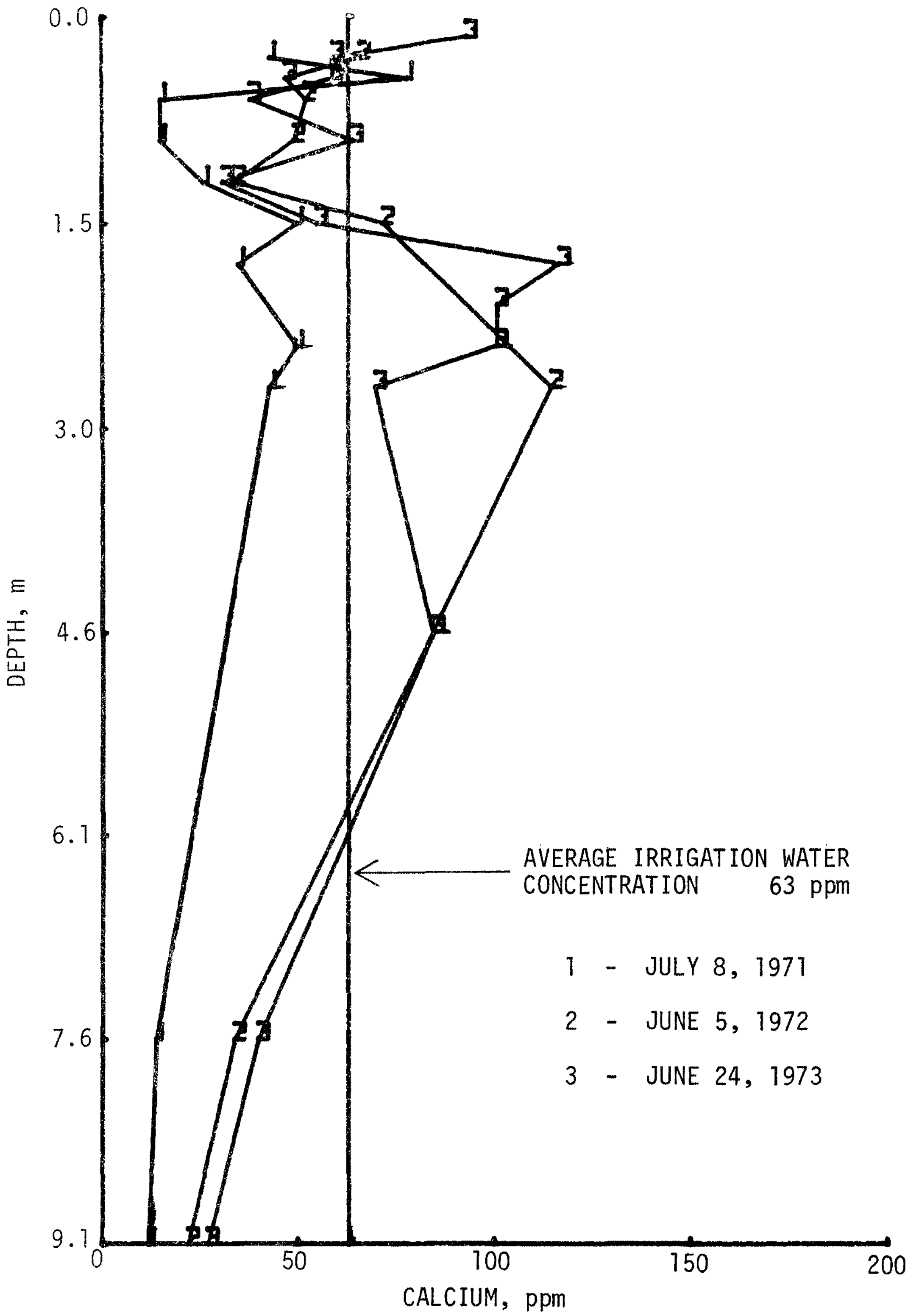


Figure 69. Calcium concentration of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a furrow irrigation system.

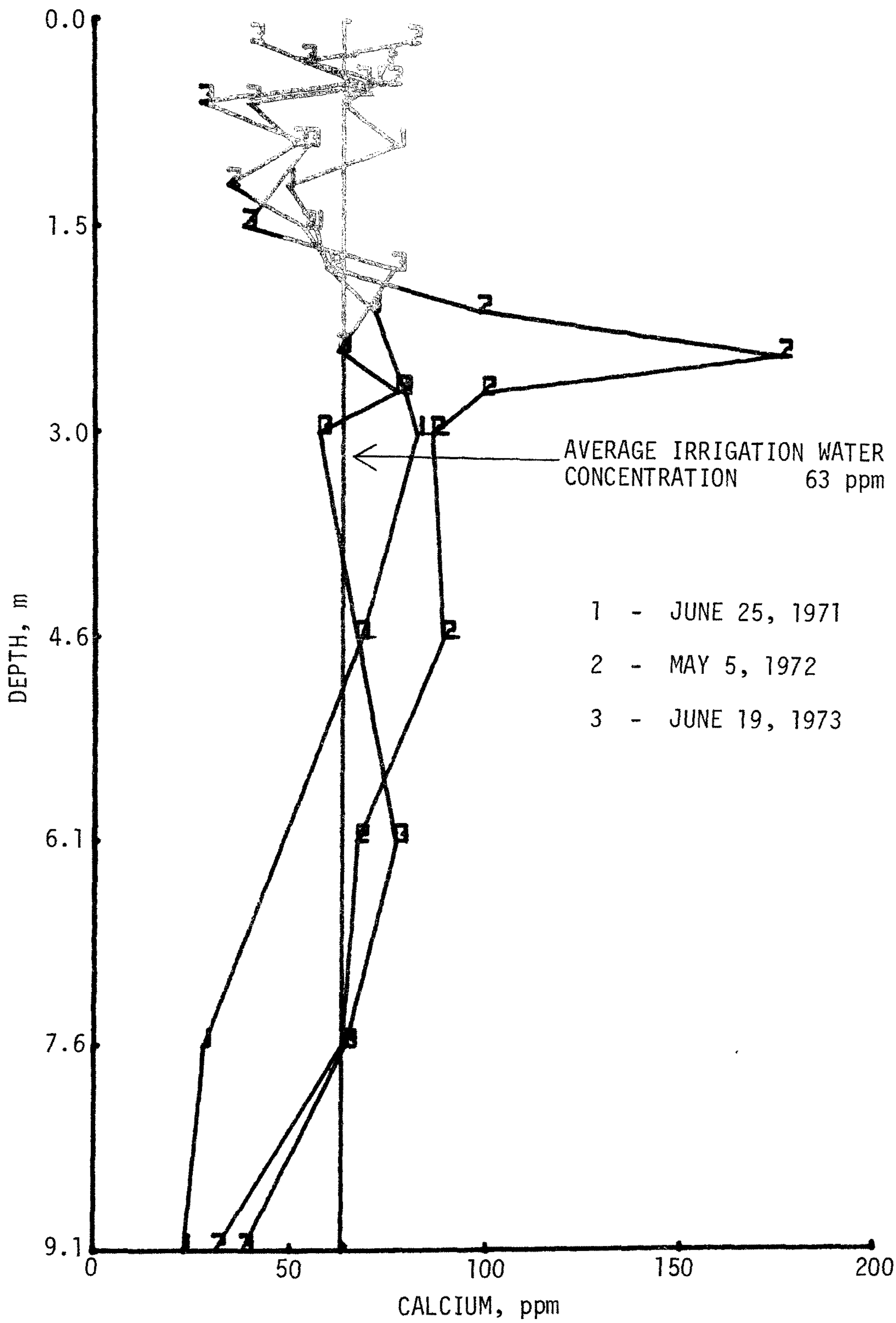


Figure 70. Calcium concentration of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a manual subirrigation system.

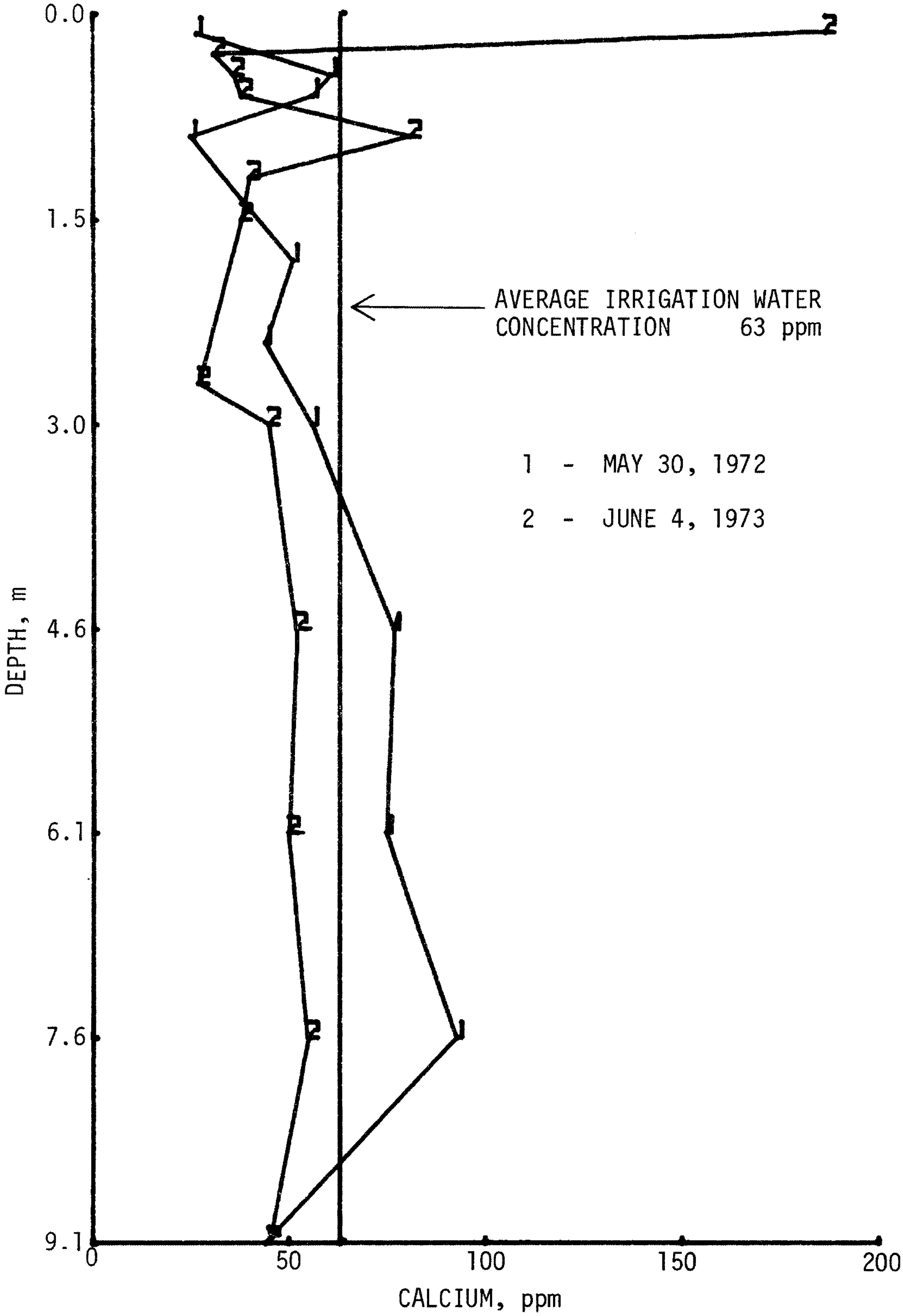


Figure 71. Calcium concentration of porous bulb soil-water extracts from various depths during 1972-1973 from an automatic subirrigation system.

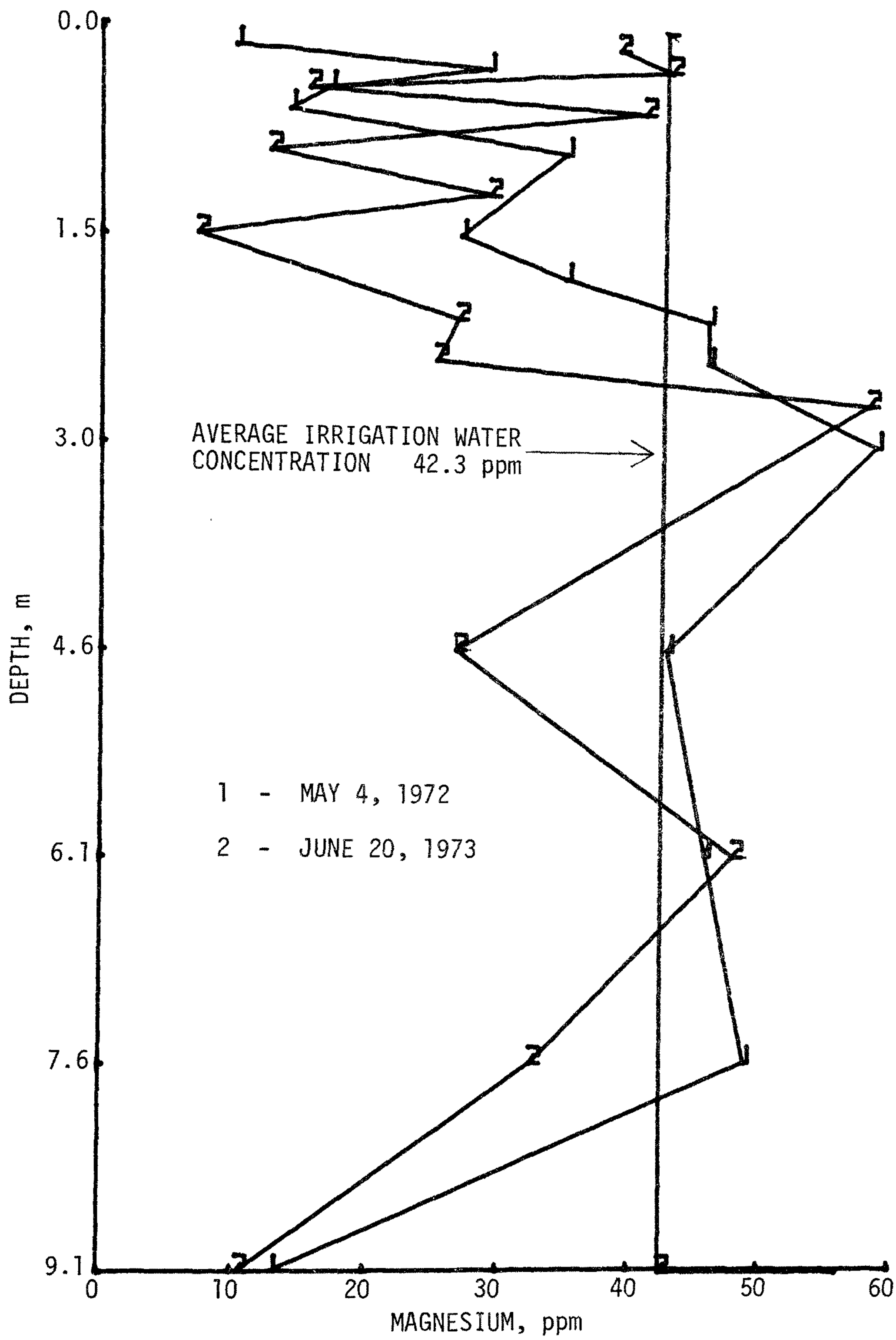


Figure 72. Magnesium concentration of porous bulb soil-water extracts from various depths during 1972-1973 from a sprinkler irrigation system.

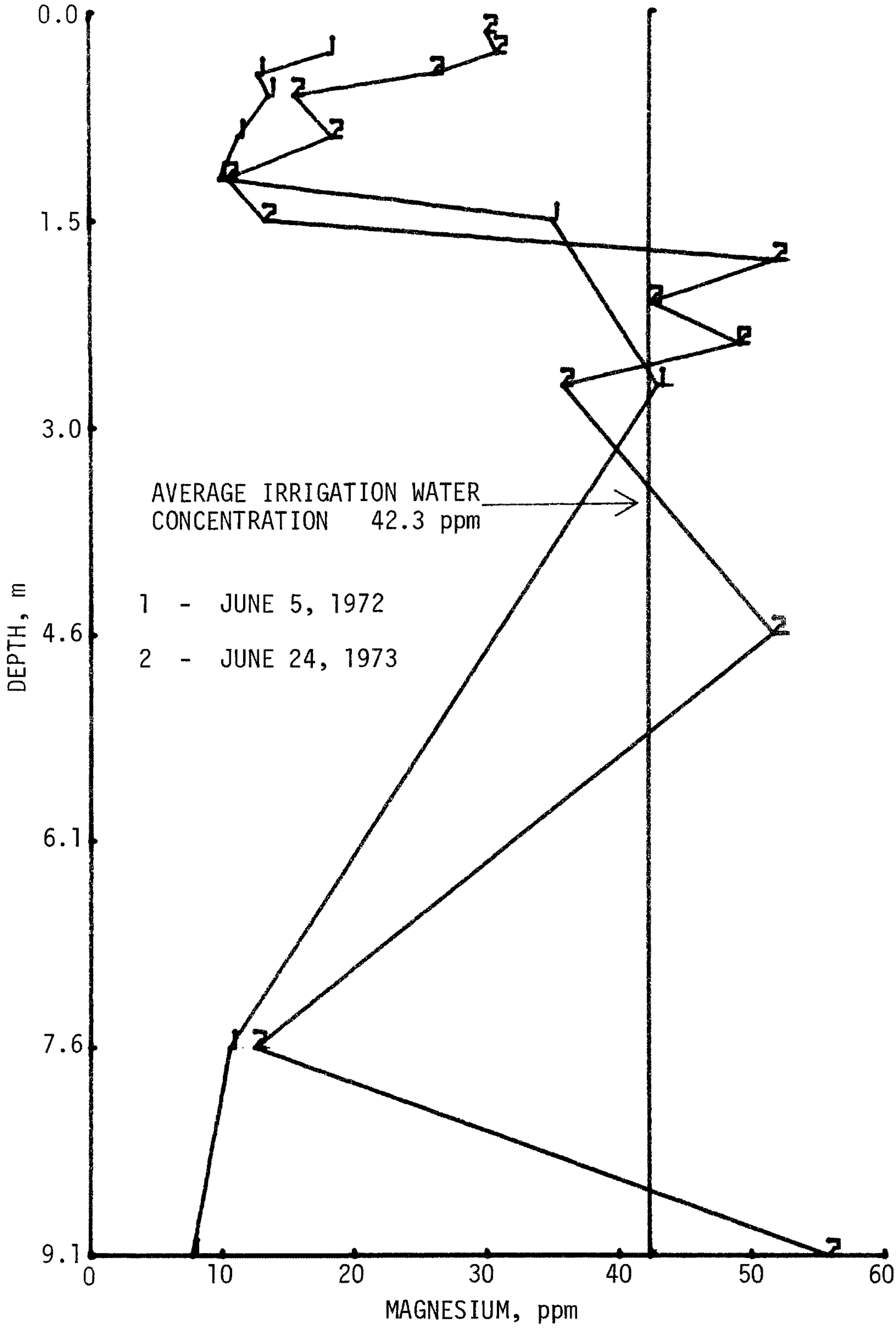


Figure 73. Magnesium concentration of porous bulb soil-water extracts from various depths during 1972-1973 from a furrow irrigation system.

the final concentrations in the profile were not as great as they were in the sprinkler irrigation system.

In the subirrigation system (Figure 74), the magnesium concentrations were similar to those obtained for other ions (Figures 55, 60, 65, and 70) in that there was a decrease at 0.6 m in the major zone of influence of the subirrigation pipe. With the exception of this depth, the magnesium concentrations increased between the surface and 2.4 m in both the manual subirrigation and automated subirrigation systems (Figure 75). Below 2.4 m, the magnesium concentration decreased under both systems. In 1973, the magnesium concentration of the extracts exceeded the concentrations of the irrigation water only at 2.1 m.

In summary, the sprinkler-irrigated plots had the highest magnesium concentrations followed by the furrow-irrigated plots with the subirrigated plots being the lowest. In general, the magnesium concentrations of the soil extracts from the root zone (0 to 1.5 m) tended to be lower than the concentrations of the irrigation water while the calcium concentrations tended to be higher than those of the irrigation water. This suggests that a portion of the magnesium applied in the irrigation water was adsorbed by the clays or precipitated to a less soluble form. None of the magnesium concentrations of the soil-water extracts from any of the systems were high enough to be of concern.

Potassium

Potassium concentrations obtained during the course of the study are shown in Figures 76 through 80. Changes that occurred during 1971 in the sprinkler irrigation system are shown in Figure 76. In general, potassium remained high in the surface meter throughout the growing season. This indicates that it was being made available at a constant rate from the soil.

Data in Figure 77 indicate somewhat of a decrease in the surface 0.9 m between 1971 and 1973 in the sprinkler-irrigation system. There is some indication of a tendency toward slight accumulations in the lower part of the profile during 1972 between 1.5 and 1.8 m. However, these concentrations were not noted in 1973. The concentrations were higher at 0.6 m in 1973 than they were in 1971 indicating the possibility of leaching. However, below 1.8 m the concentrations were slightly less or approximately equal to those of the irrigation water following the first year of the study. No massive amounts of leaching were occurring compared to the amounts produced in the surface, indicating that the excess potassium may have reacted with the clay.

Data from the furrow irrigation system indicate little change (Figure 78). This plot was land leveled; consequently, part of the micaceous minerals which were high in potassium was probably removed from the surface and the potassium in solution in the resulting top soil is not as great as that top soil which was removed. In general, the potassium concentrations below 1.5 m were approximately equal to that of the irrigation water, 2.8 ppm.

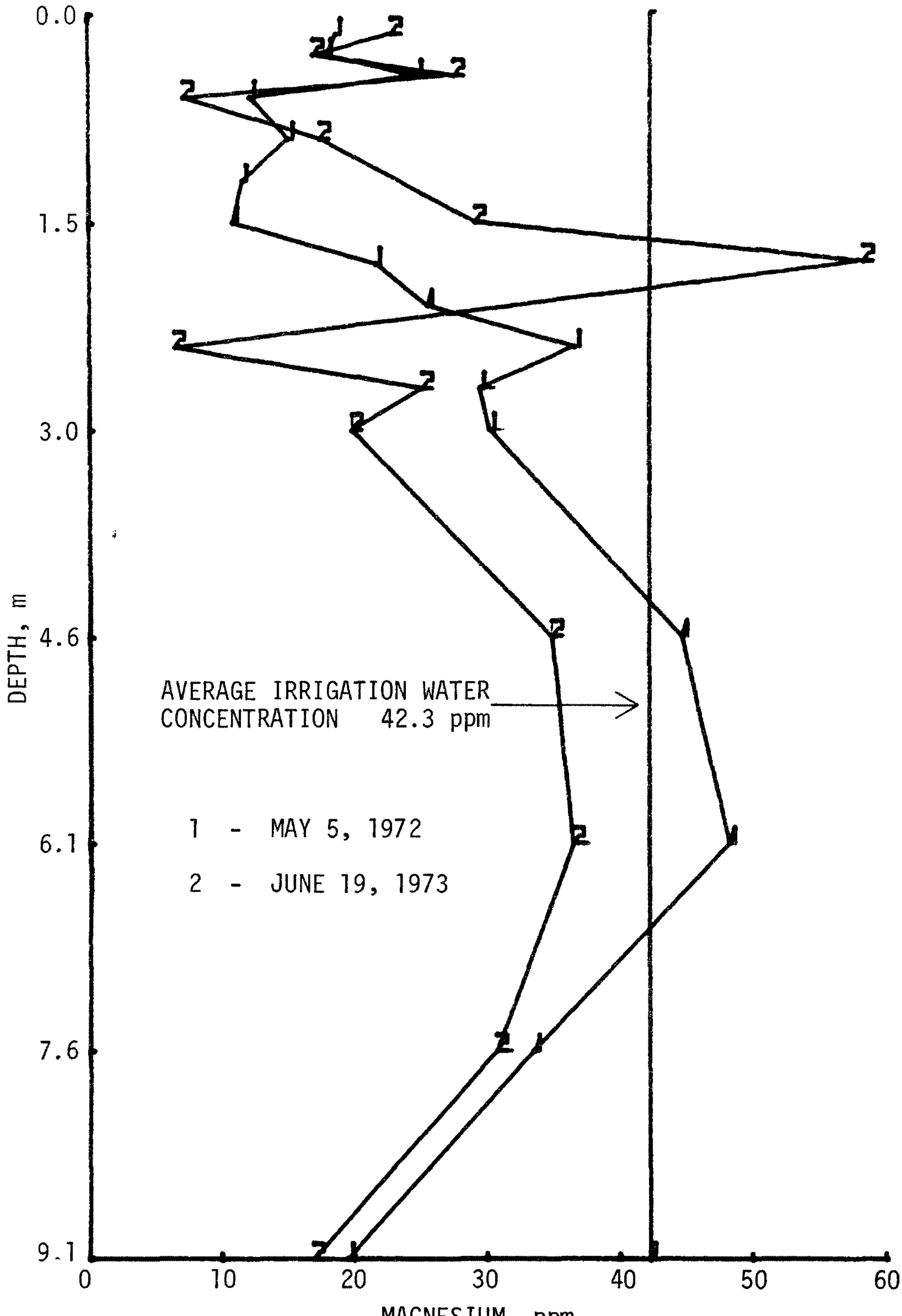


Figure 74. Magnesium concentration of porous bulb soil-water extracts from various depths during 1972-1973 from a manual subirrigation system.

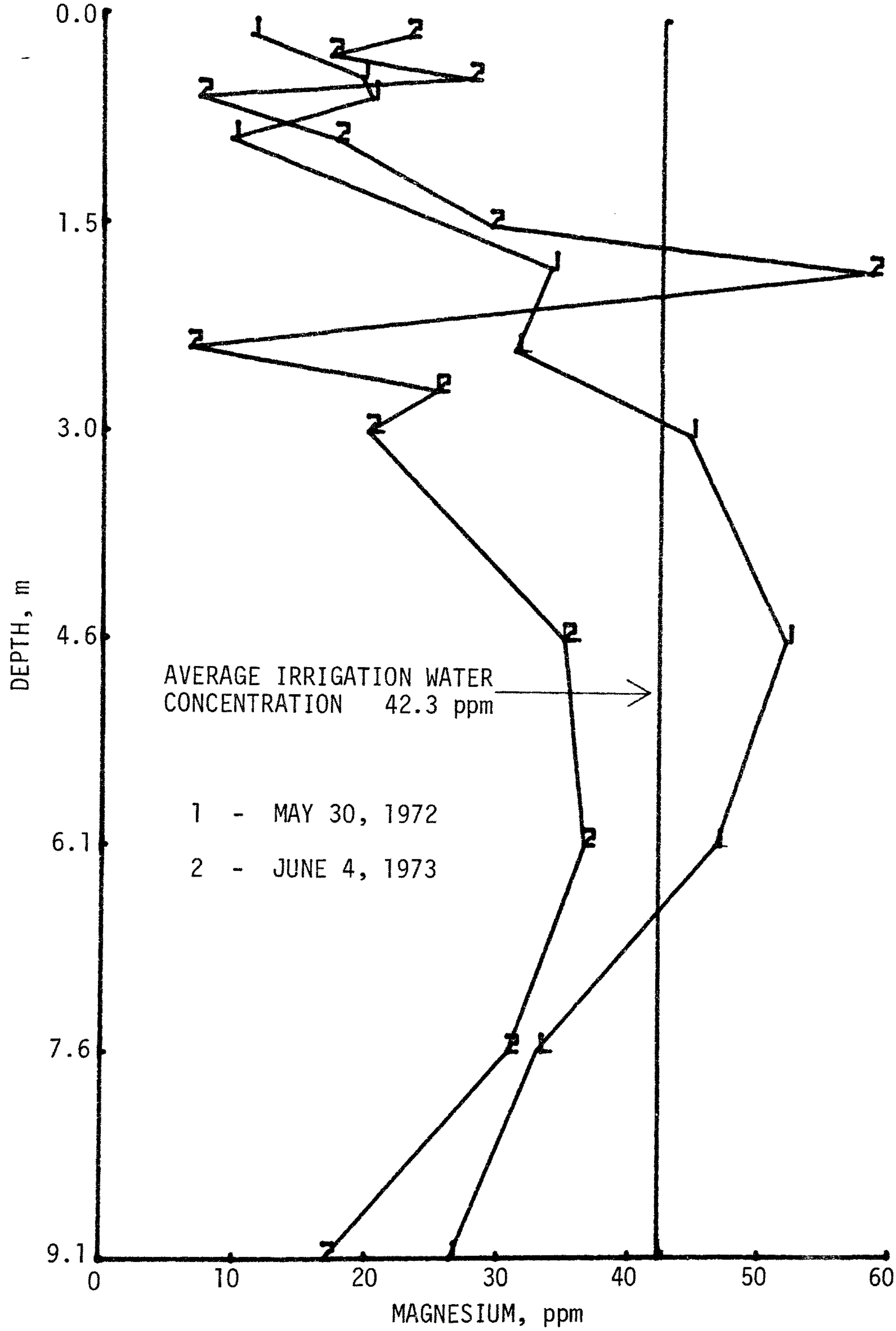


Figure 75. Magnesium concentration of porous bulb soil-water extracts from various depths during 1972-1973 from an automatic subirrigation system.

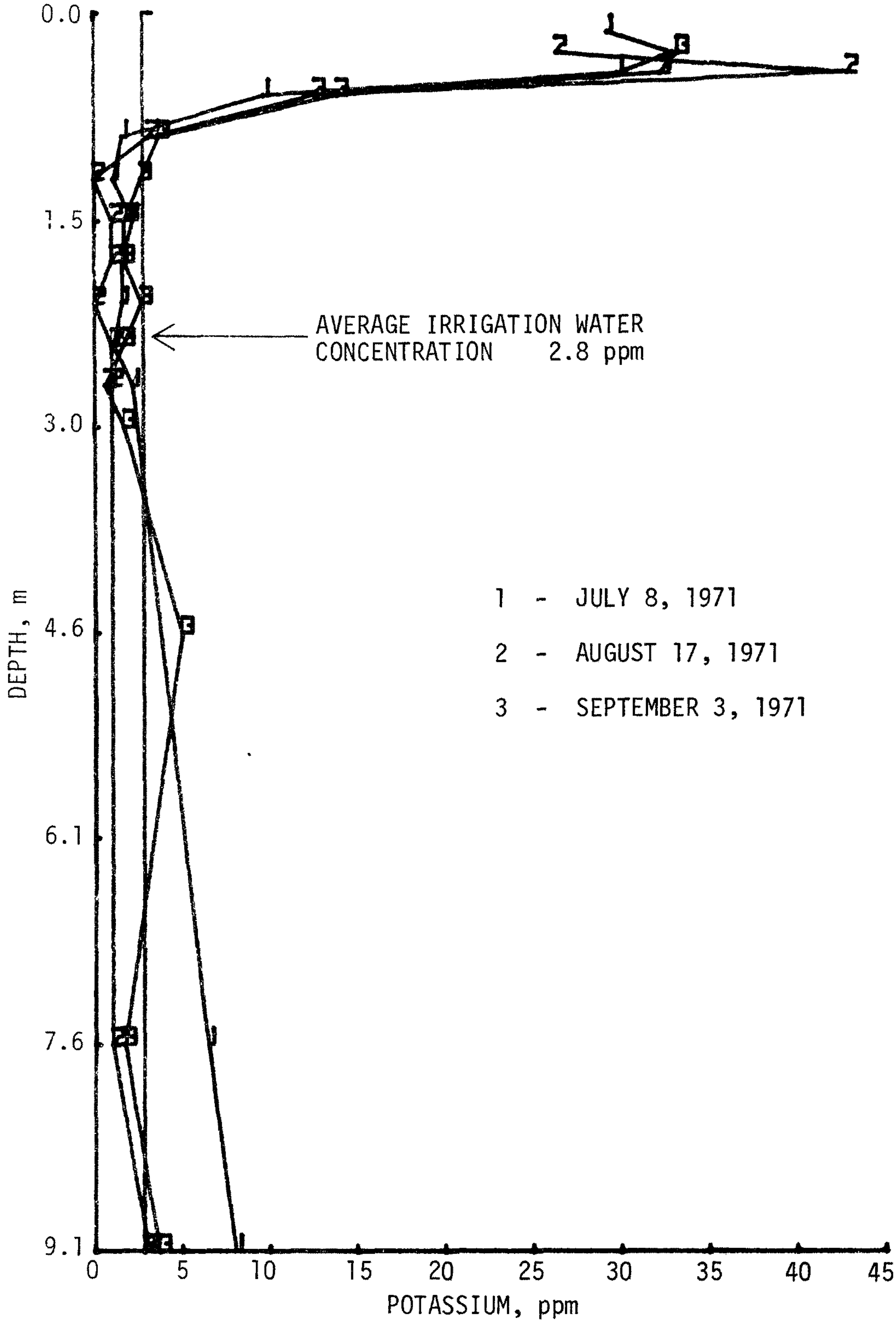


Figure 76. Potassium concentration of porous bulb soil-water extracts from various depths during 1971 from a sprinkler irrigation system.

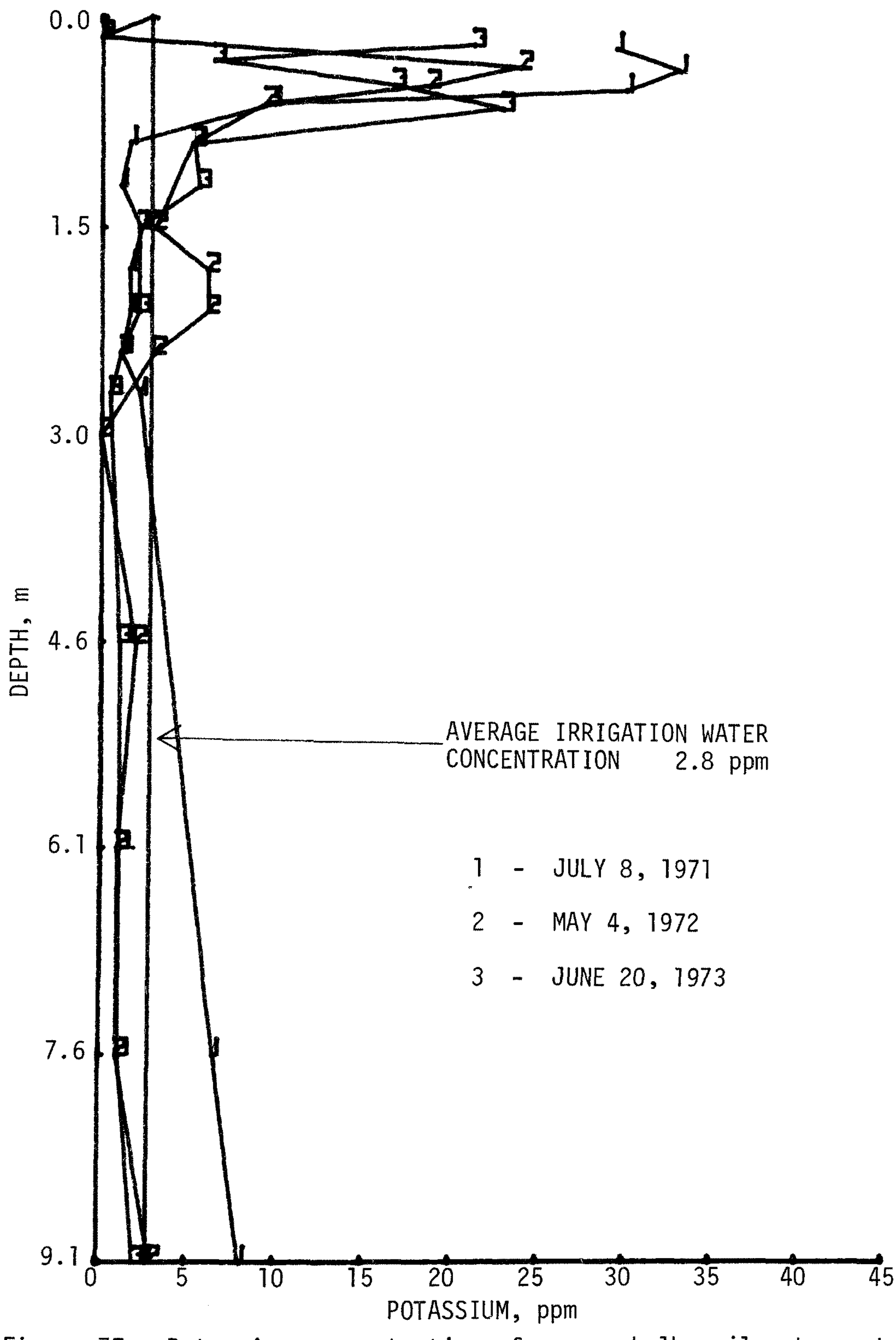


Figure 77. Potassium concentration of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a sprinkler irrigation system.

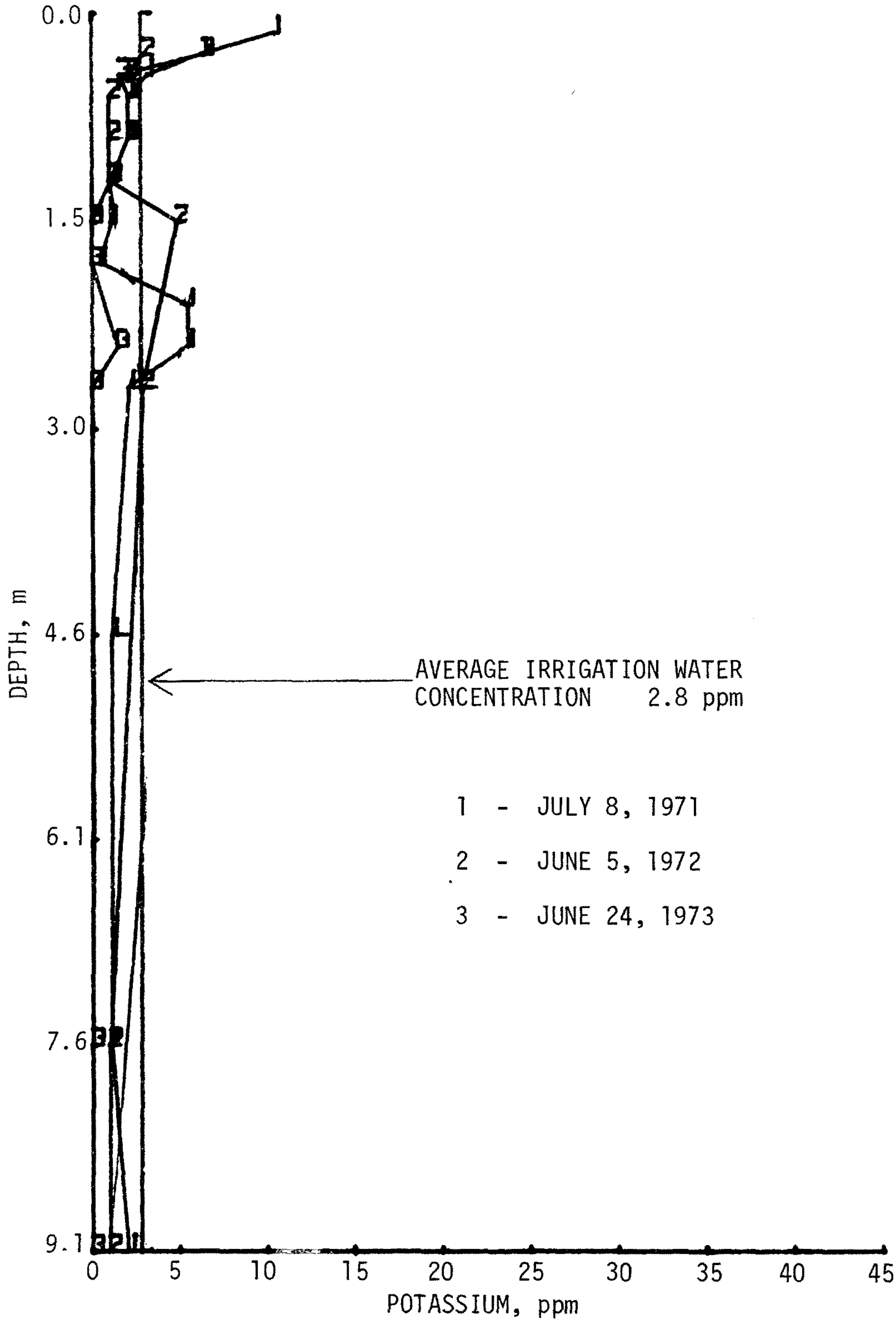


Figure 78. Potassium concentration of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a furrow irrigation system.

The subirrigation system (Figure 79) yielded data very similar to the sprinkler irrigation system (Figure 77) in that there was a decrease in the potassium concentration at the surface between 1971 and 1973. There was a slight increase at 1.8 to 2.1 m indicating some movement out of the zone around the subirrigation line to this particular area. The decreases in the surface were greater than that of the sprinkler-irrigated plot, indicating that the surface may have been drier with less moisture available to make the potassium available.

The same trend holds for the automated subirrigation system (Figure 80) in that the surface remained higher with a zone of low concentration at 0.6 m. There was some indication that there was an increase in potassium concentrations at 0.9 to 1.8 m, indicating again some movement out of the zone where the subirrigation pipe was located.

In summary, the greatest potassium concentrations were sprinkler irrigation system followed by the manual subirrigation system, automated subirrigation and furrow irrigation system. Soil minerals are indicated to play a major role in the production of potassium in that the land leveled furrow irrigation system had very low potassium concentrations in the soil solution.

Ammonium

Typical ammonium-N concentrations found during the course of the study are shown in Figures 81 through 84. Changes that occurred during 1971 in a sprinkler plot to which Uran was chisel-applied are shown in Figure 81. Concentrations were generally low at all sampling points and dates with the exception of samples obtained on August 17 and September 3 at 6.1 m.

Data for the same plot for sampling dates in 1971, 1972, and 1973 are shown in Figure 82. Concentrations of ammonium-N were uniformly low except for 1.2 and 6.1 m on May 4, 1972. By June 20, 1973, concentrations measured at these depths were similar to those at other depths.

Ammonium-N concentrations found in a furrow-irrigated plot treated with Uran banded in the bed at a level above the bottom of the water furrow for three sampling dates are shown in Figure 83. Concentrations were again generally low with only two samples having concentrations exceeding 3.0 ppm. These were at 1.5 and 2.1 m on May 8, 1972.

Data from a similarly treated manually-subirrigated plot shown in Figure 84 indicate a similar trend as found in the two previously discussed systems. Ammonium-N concentrations were generally low except for isolated samples (e.g., 0.6 and 2.4 m on July 8, 1971; and 0.9, 1.8, 2.4, 4.6, and 7.6 m on May 5, 1972).

In summary, while there was some evidence of ammonium-N in the profile below the root zone, the inconsistency with which it was found in concentrations above 3.0 ppm make assessment of movement impossible. Generally, ammonium-N concentrations were uniformly low and would appear to be of little consequence from the standpoint of irrigation return flow degradation.

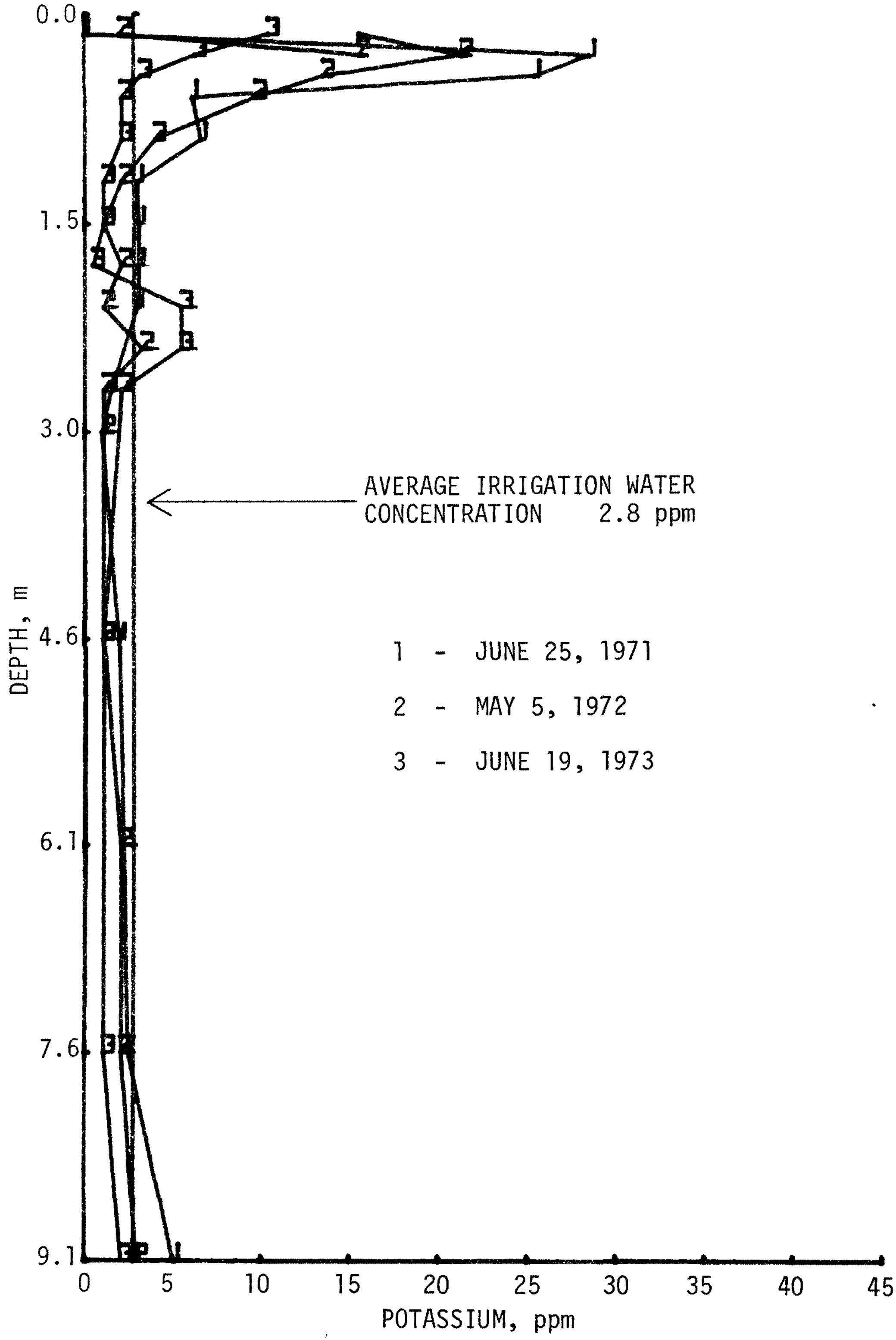


Figure 79. Potassium concentration of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a manual subirrigation system.

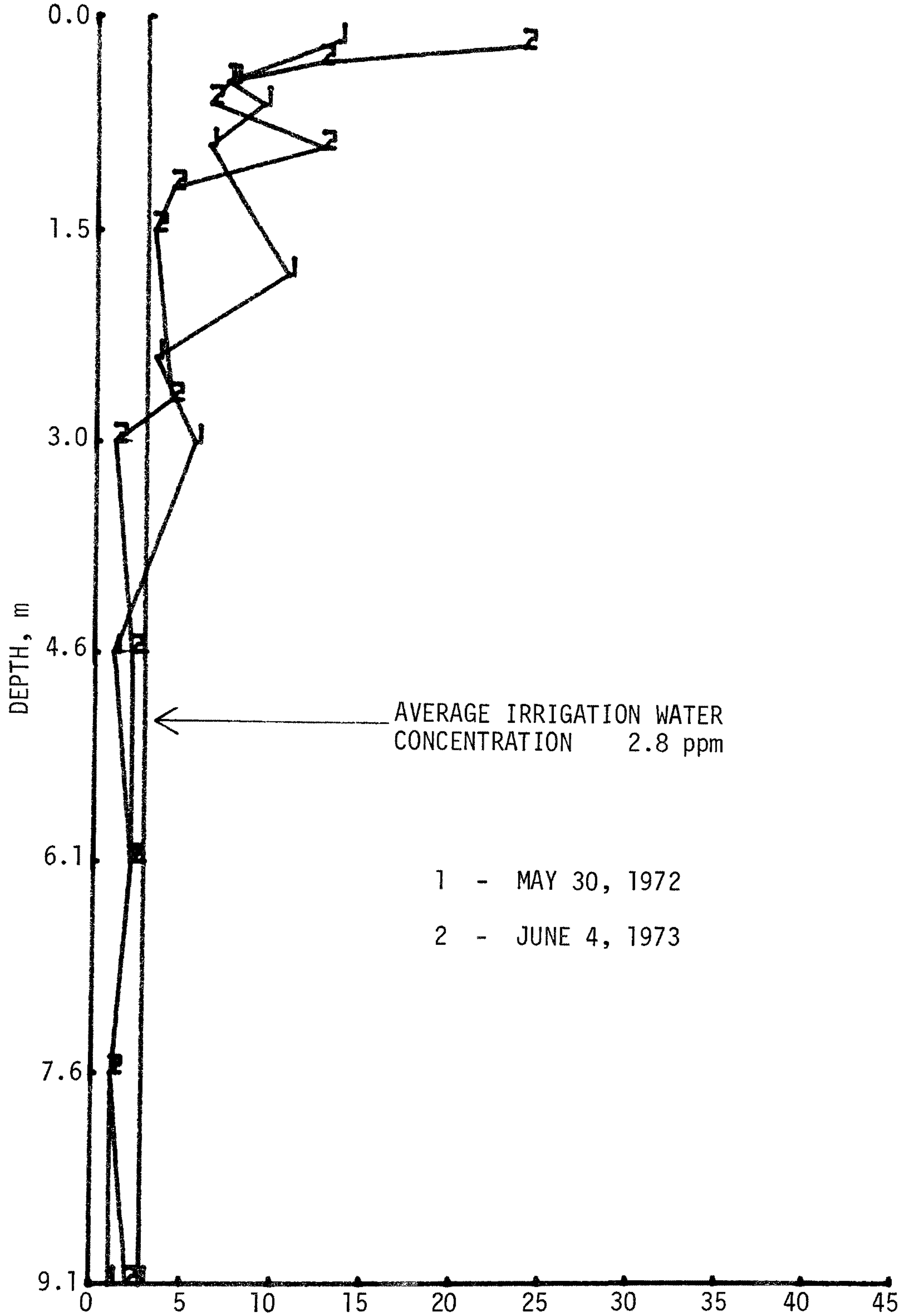


Figure 80. Potassium concentration of porous bulb soil-water extracts from various depths during 1972-1973 from an automatic subirrigation system.

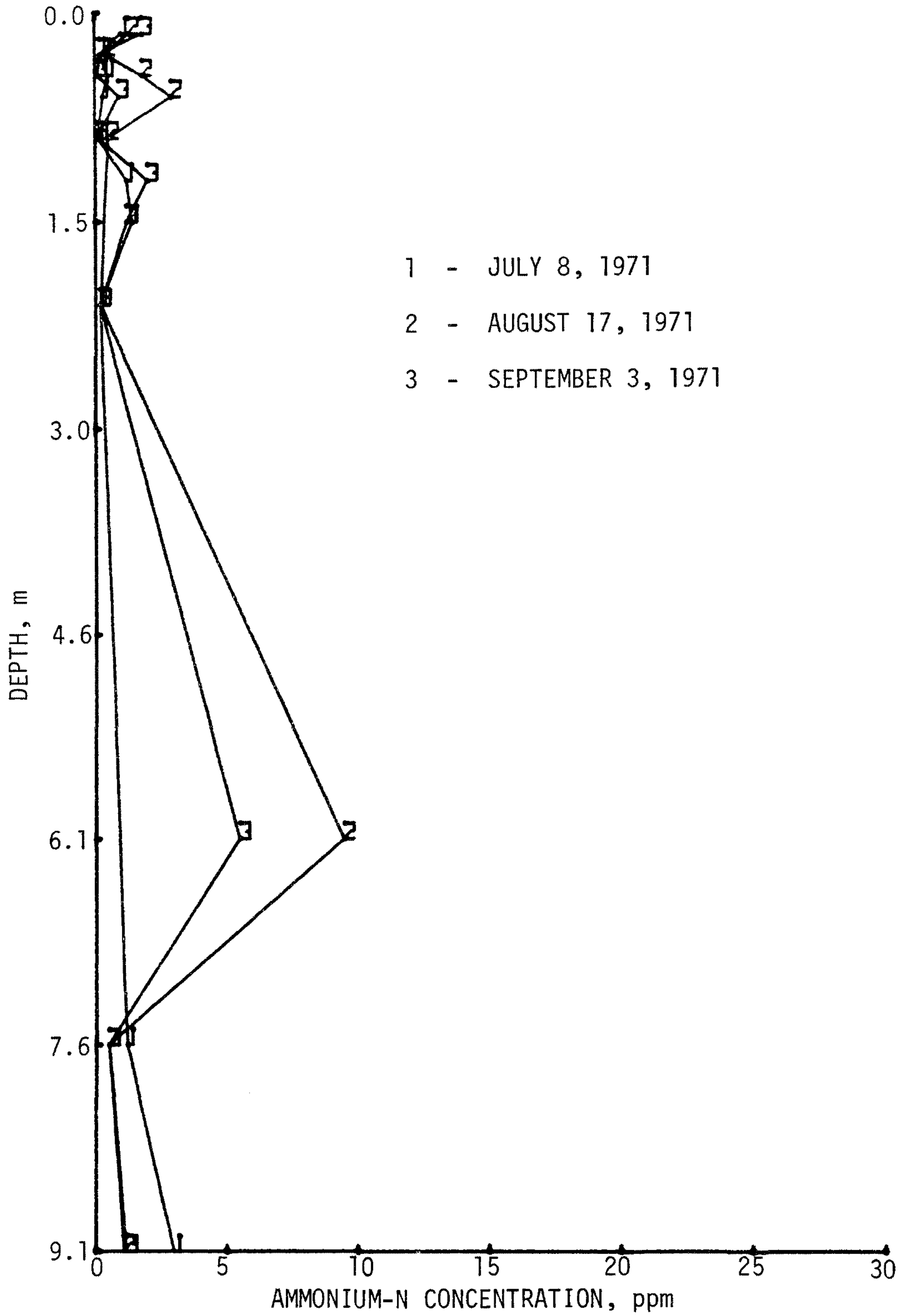


Figure 81. Ammonium-N concentrations of porous bulb soil-water extracts from various depths during 1971 from a sprinkler-irrigated plot fertilized with Uran banded in the bed.

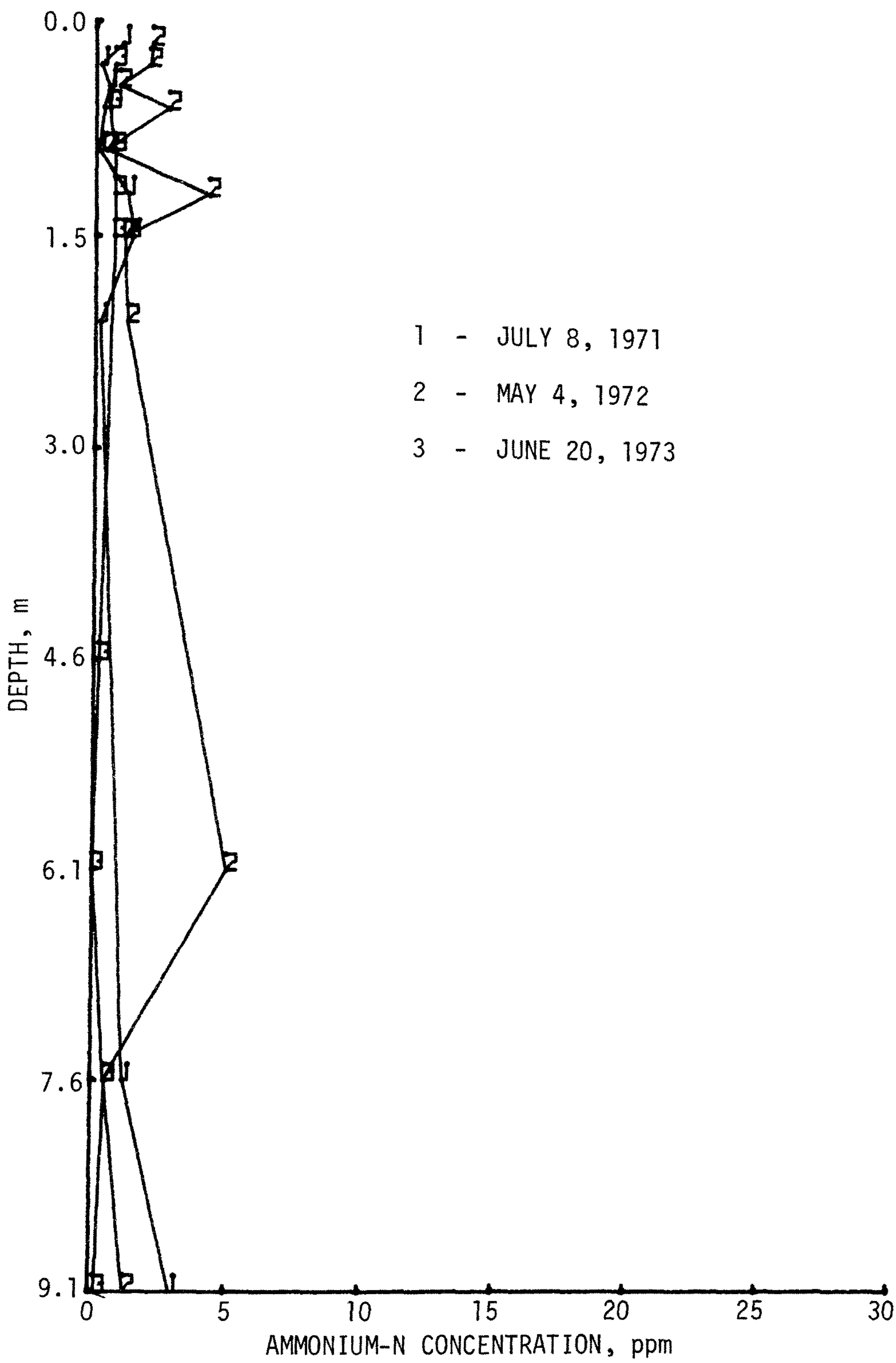


Figure 82. Ammonium-N concentrations of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a sprinkler-irrigated plot fertilized with Uran banded in the bed.

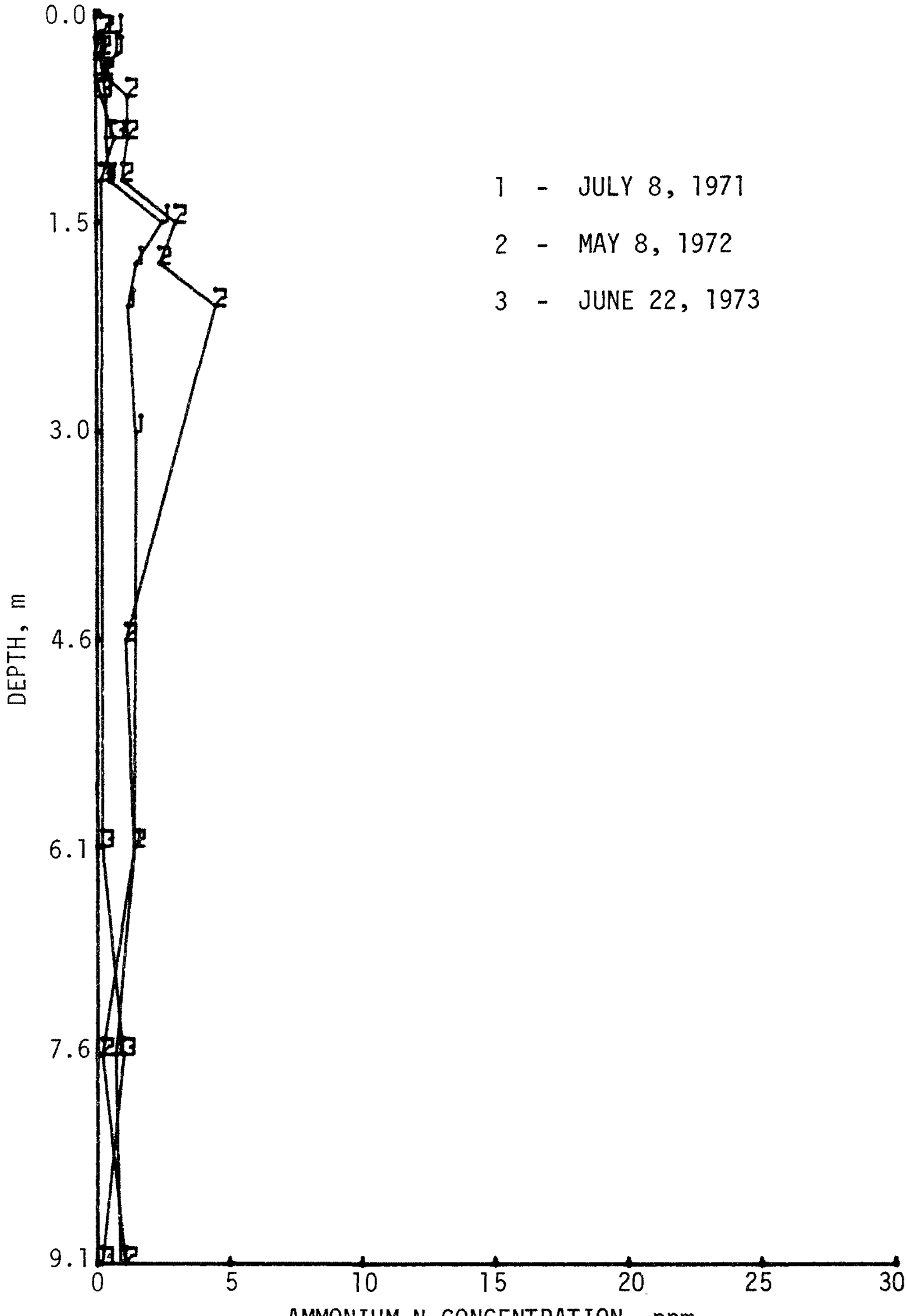


Figure 83. Ammonium-N concentrations of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a furrow-irrigated plot fertilized with Uran banded in the bed.

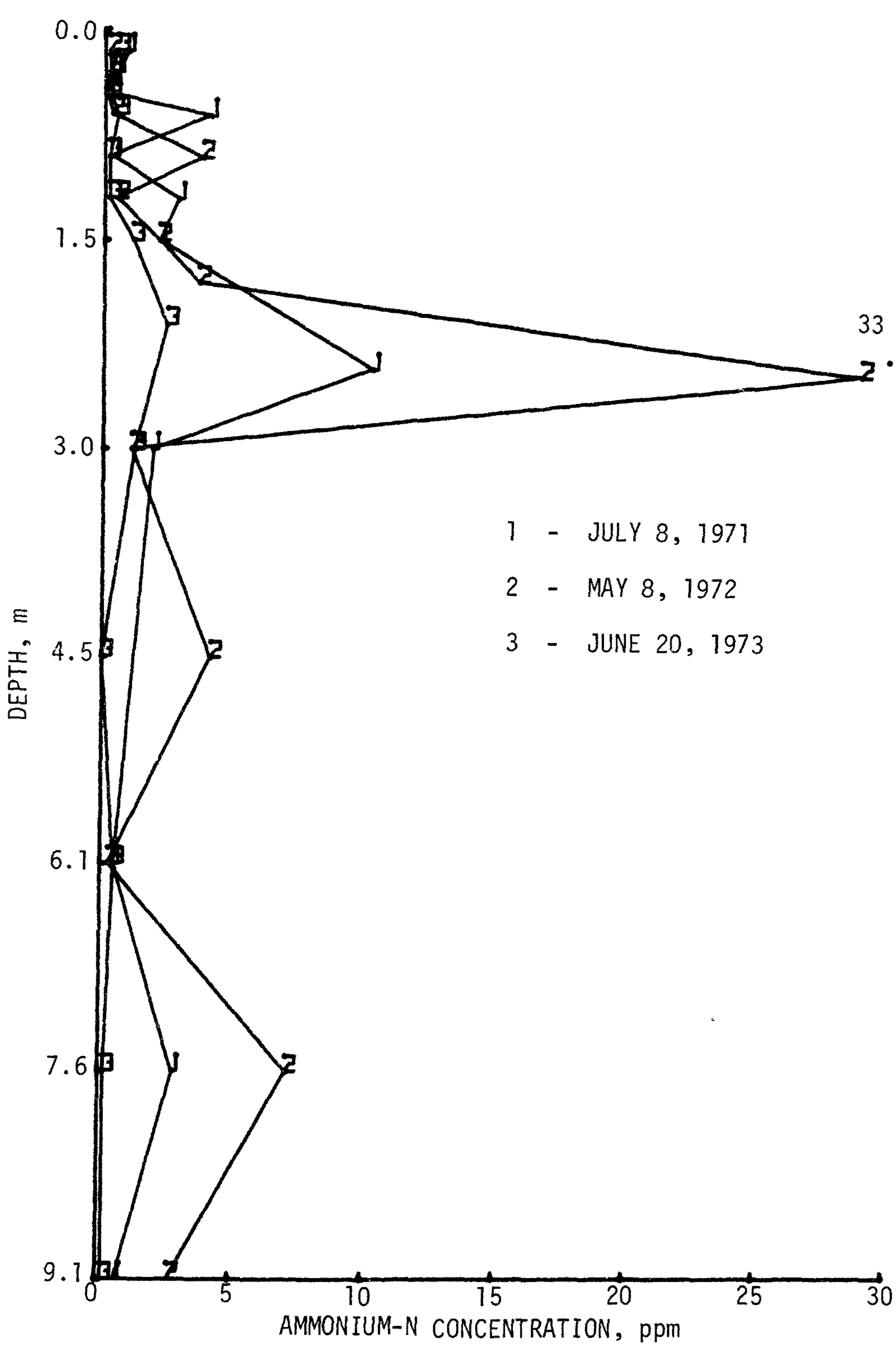


Figure 84. Ammonium-N concentrations of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a manually-subirrigated plot fertilized with Uran banded in the bed.

Conductivity

Conductivities of soil-water extracts for the various irrigation systems during the three years of the study are given in Figures 85 through 89. In general, the conductivity of the soil-water extracts was less than the conductivity of the irrigation water applied during 1971 for sprinkler irrigation (Figure 85). The peak at 0.9 m on September 3 is somewhat related to the calcium concentration (Figure 67). Between the beginning and end of the measurement period the conductivity decreased at depths below 3.0 m.

Between 1971 and 1973 there was a slight increase in the conductivity of the 0 to 1.5-m zone, little change between 1.5 and 3.0 m, and a decrease below 3.0 m in the sprinkler irrigation system (Figure 86). There was little discernible change in conductivity of soil-water extracts of the furrow irrigation system (Figure 87). In the manual subirrigation system (Figure 88), there was a decrease at 0.15 and 0.9 m and increases at 1.5 and 1.8 m. Other changes were minimal. In the automated subirrigation system (Figure 89), there was an overall decrease in conductivity so that, throughout the soil profile, the values in 1973 were all less than for the irrigation water applied.

In summary, the conductivity was highest in the sprinkler irrigation system with the furrow irrigation and manual subirrigation systems being intermediate and the automated subirrigation system being the lowest. Since most values were lower than the average irrigation water conductivity of 947 µmhos, it was concluded that the salt load in the irrigation return flow was not a potential pollution hazard under the conditions of this study.

This concludes an overall discussion of the ions measured and conductivity with the exception of nitrate. Since nitrate was higher in the soil-water extracts and is a major item of concern in the area, it will be discussed in more detail than the other ions. Since none of the above ions are indicated to be degrading the quality of the irrigation return flow in these particular soils, no further discussion of these ions will be undertaken. The discussion of nitrate in soil samples and porous bulb soil-water extracts follows.

Nitrate

Control or Unfertilized Plots--

Average nitrate-N concentration of the irrigation water was 6.7 ppm. As would be suspected, much higher values for nitrate-N were noted in the control plots throughout the study due to nitrate-N mineralized from the soil and plant material. Values for the sprinkler-irrigated plots (Figure 90) and furrow-irrigated plots (Figures 91 and 92) are typical of those obtained during the growing season in 1973. In the sprinkler-irrigated plot (Figure 90), concentrations of 50-ppm nitrate-N were obtained on June 4 at 2.1 m. A movement of nitrate-N was indicated by concentration decreases from 0 to 0.9 m, increases at 1.5 m, decreases at 2.1 m, and increases at 4.6 m as the season progressed. A similar movement was noted in one of the furrow-irrigated control plots (Figure 91) as the nitrate-N

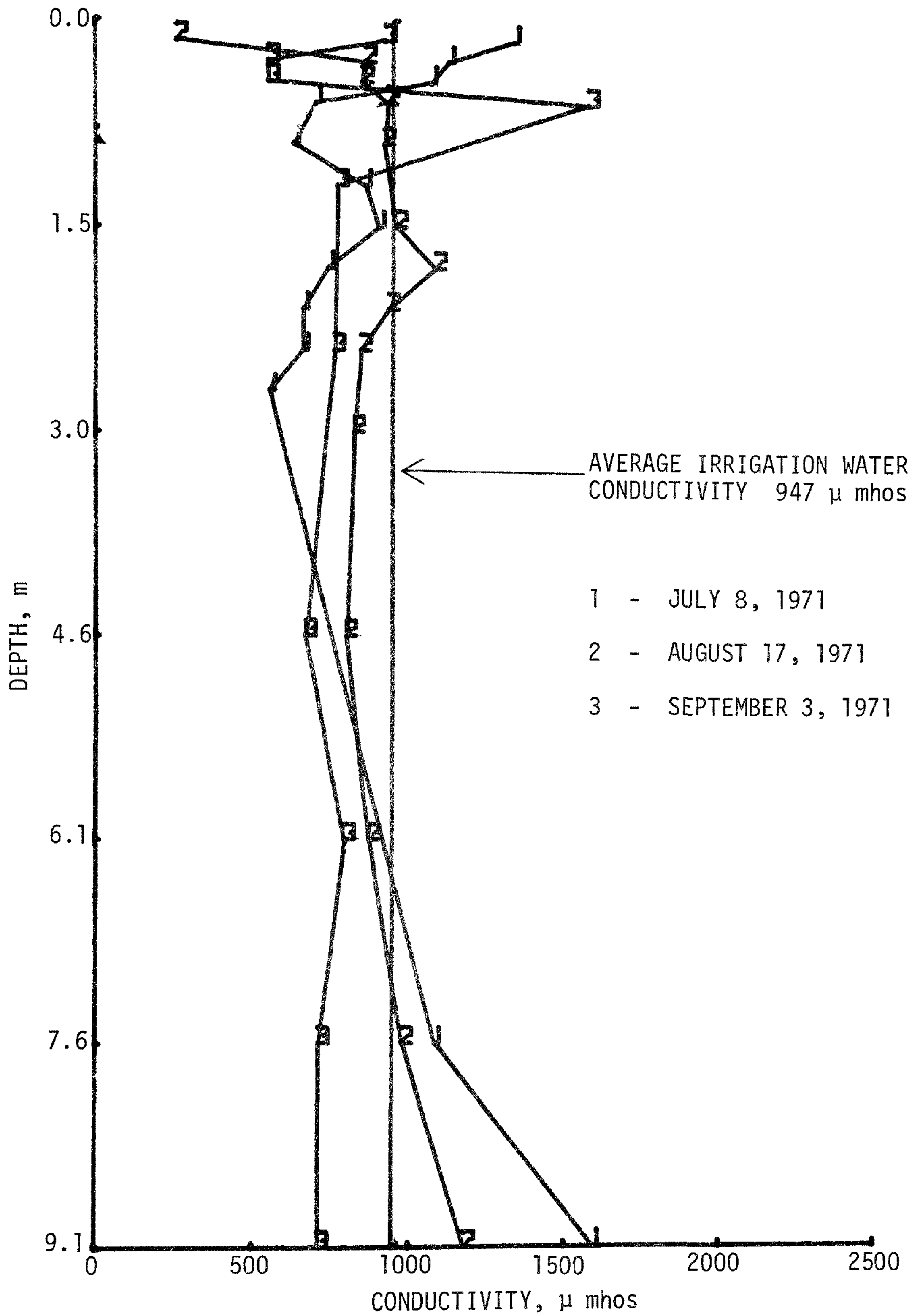


Figure 85. Electrical conductivity of porous bulb soil-water extracts from various depths during 1971 from a sprinkler irrgation system.

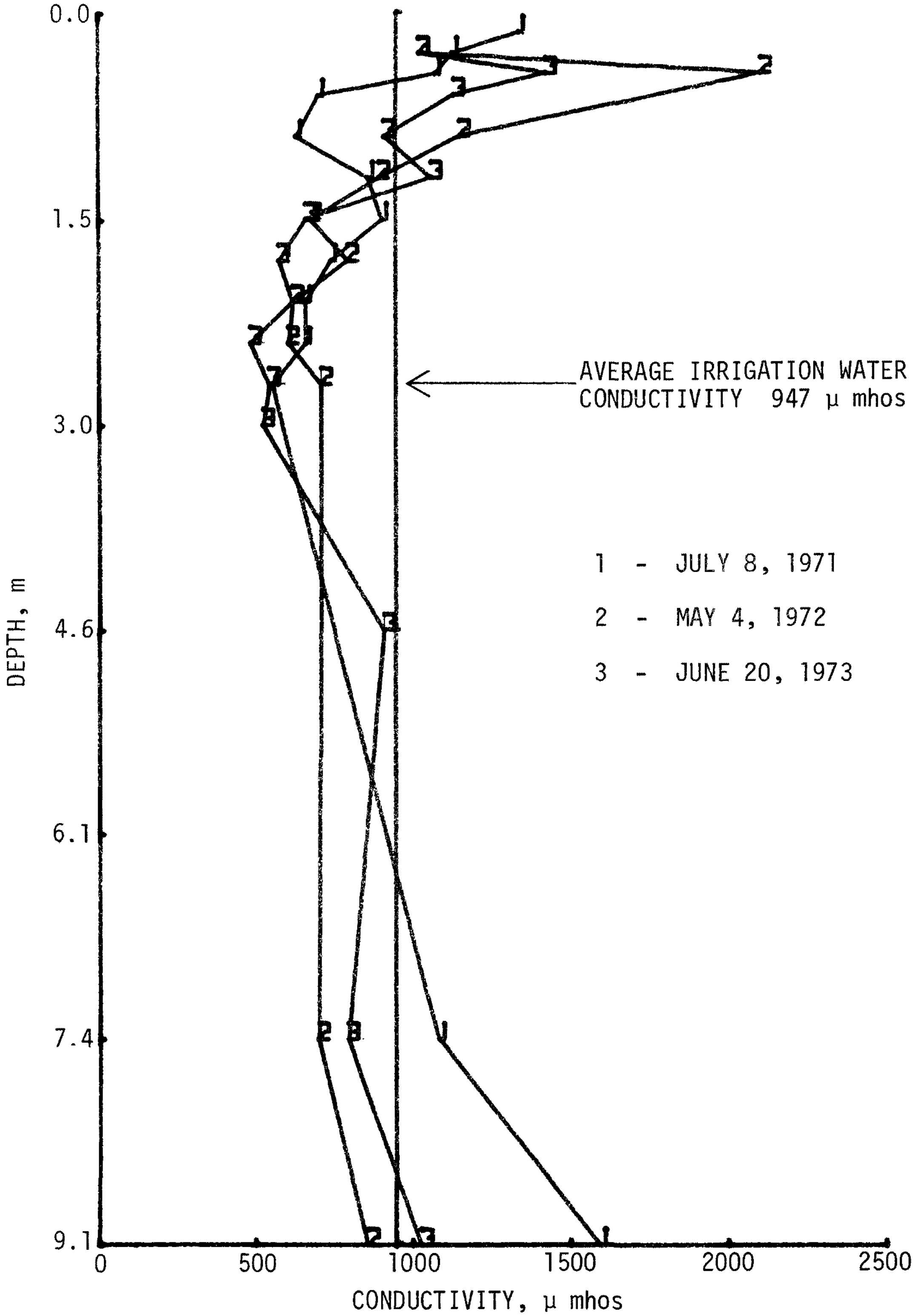


Figure 86. Electrical conductivity of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a sprinkler irrigation system.

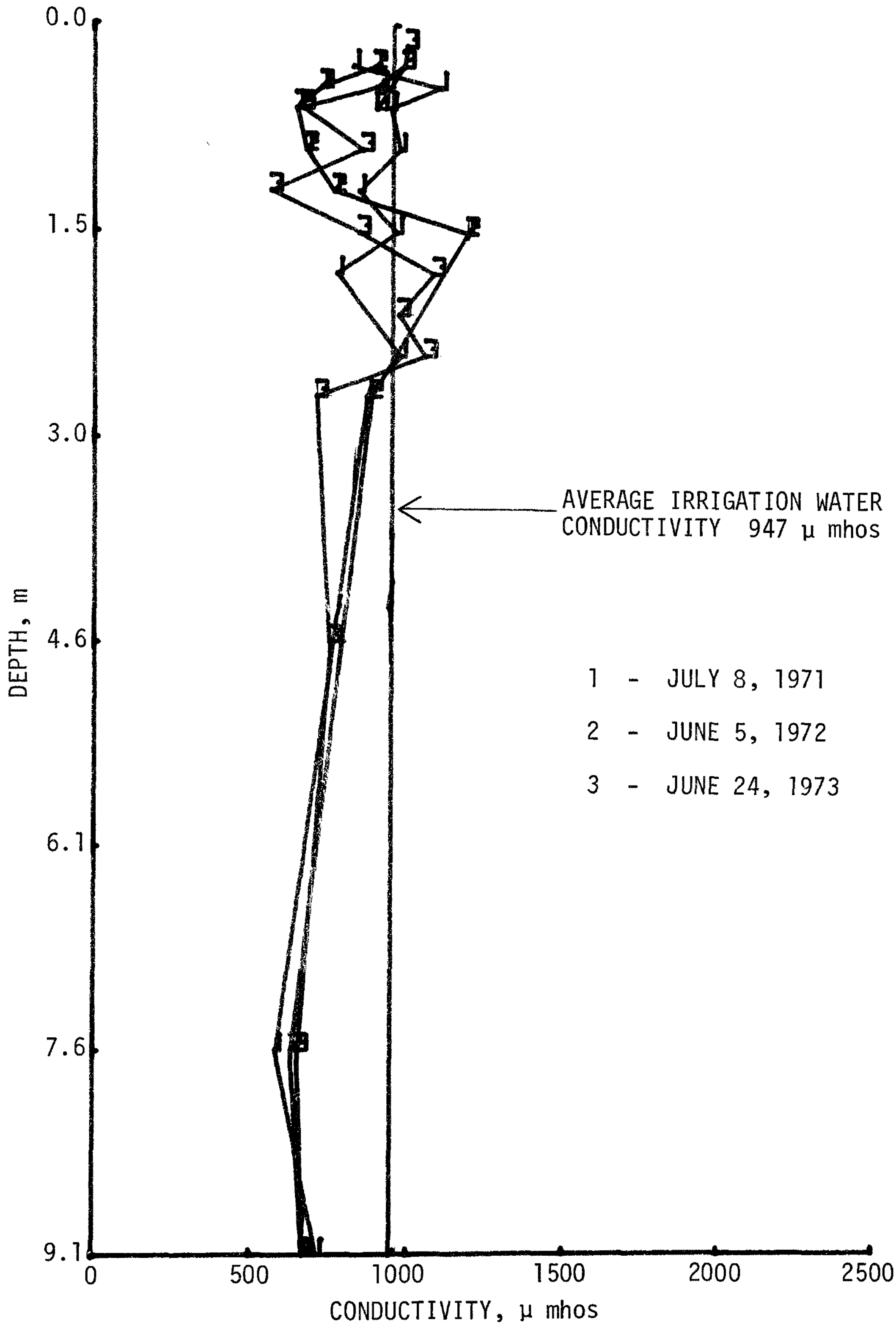


Figure 87. Electrical conductivity of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a furrow irrigation system.

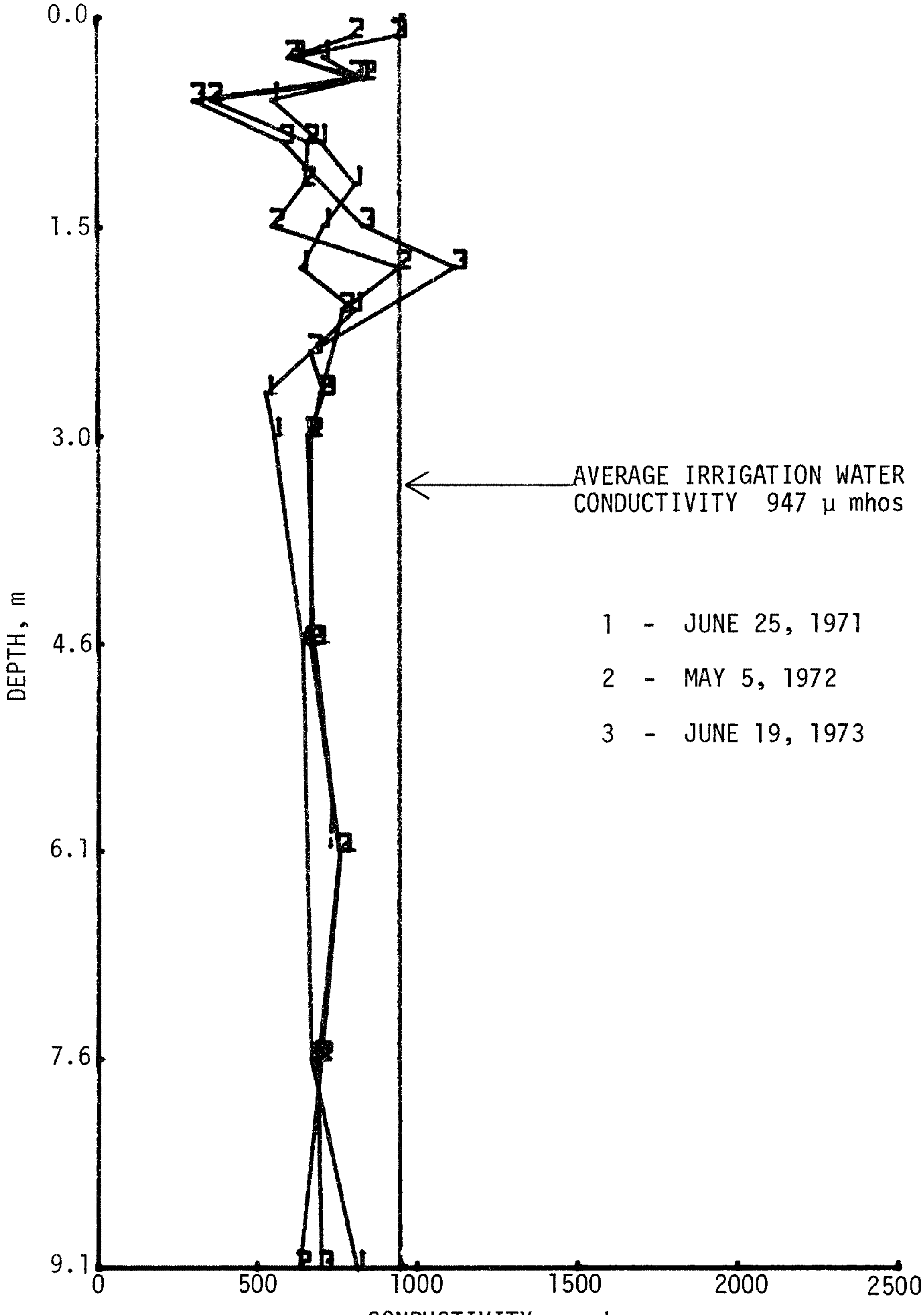


Figure 88. Electrical conductivity of porous bulb soil-water extracts from various depths during 1971, 1972 and 1973 from a manual subirrigation system.

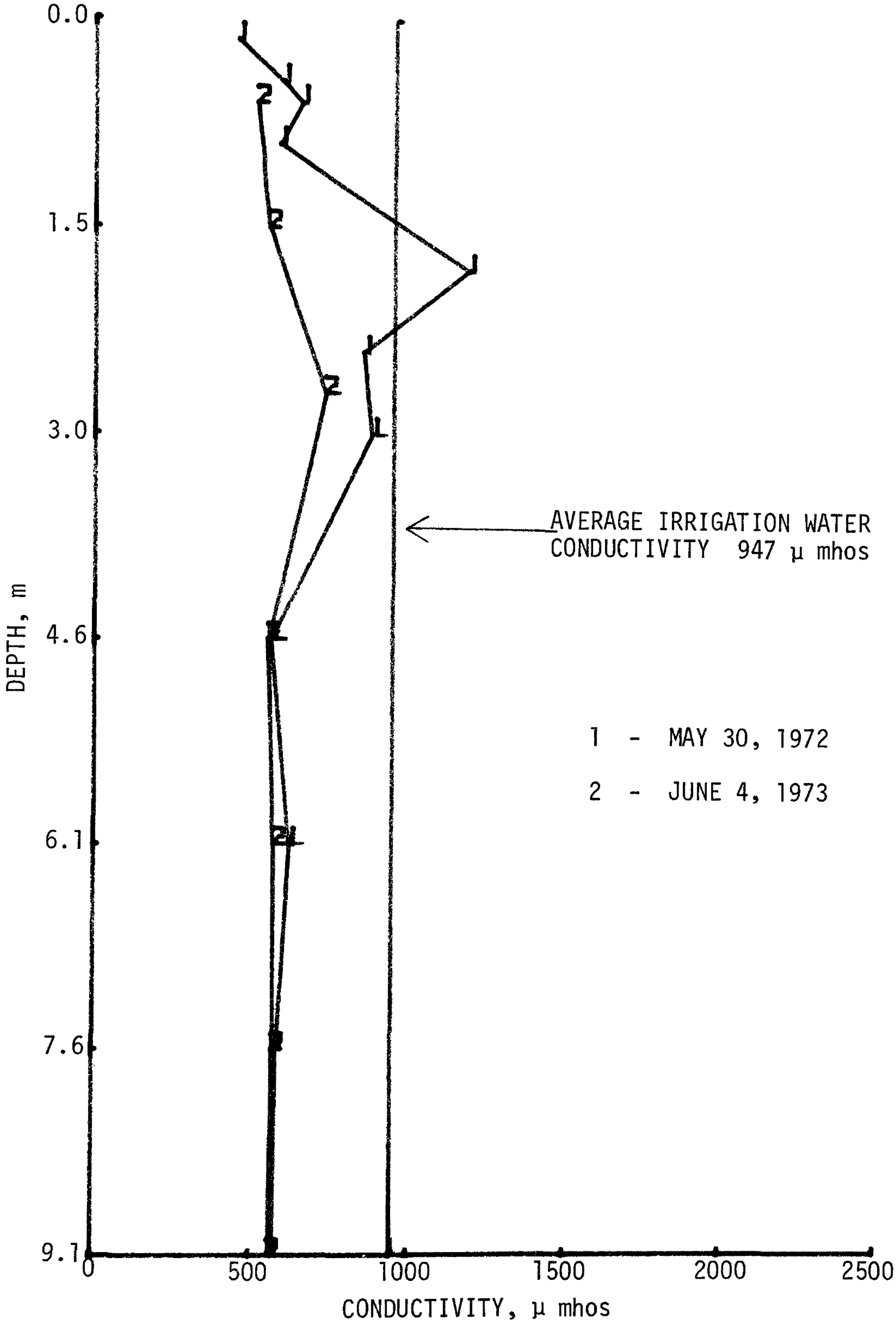


Figure 89. Electrical conductivity of porous bulb soil-water extracts from various depths during 1972-1973 from an automatic subirrigation system.

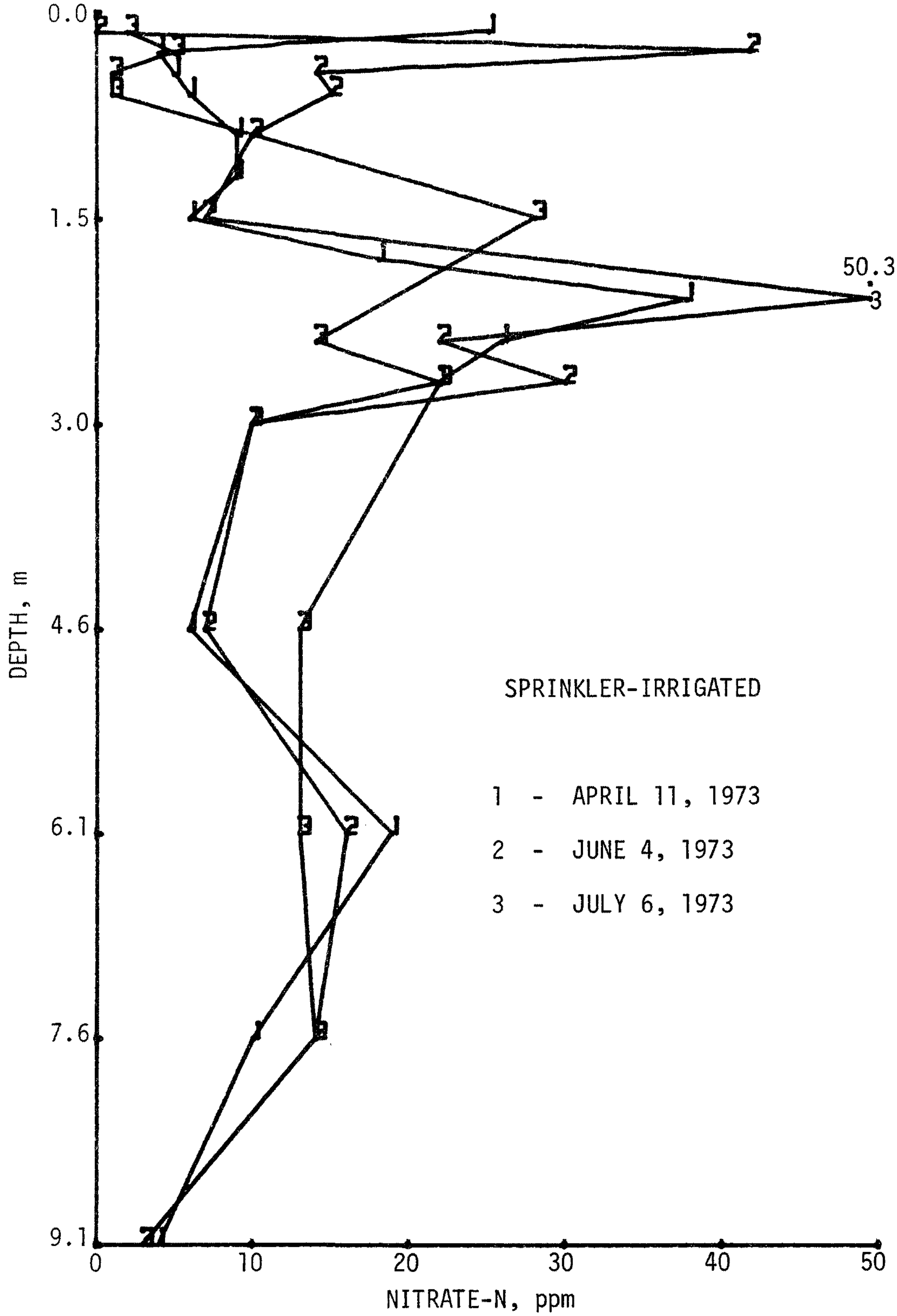


Figure 90. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a control plot.

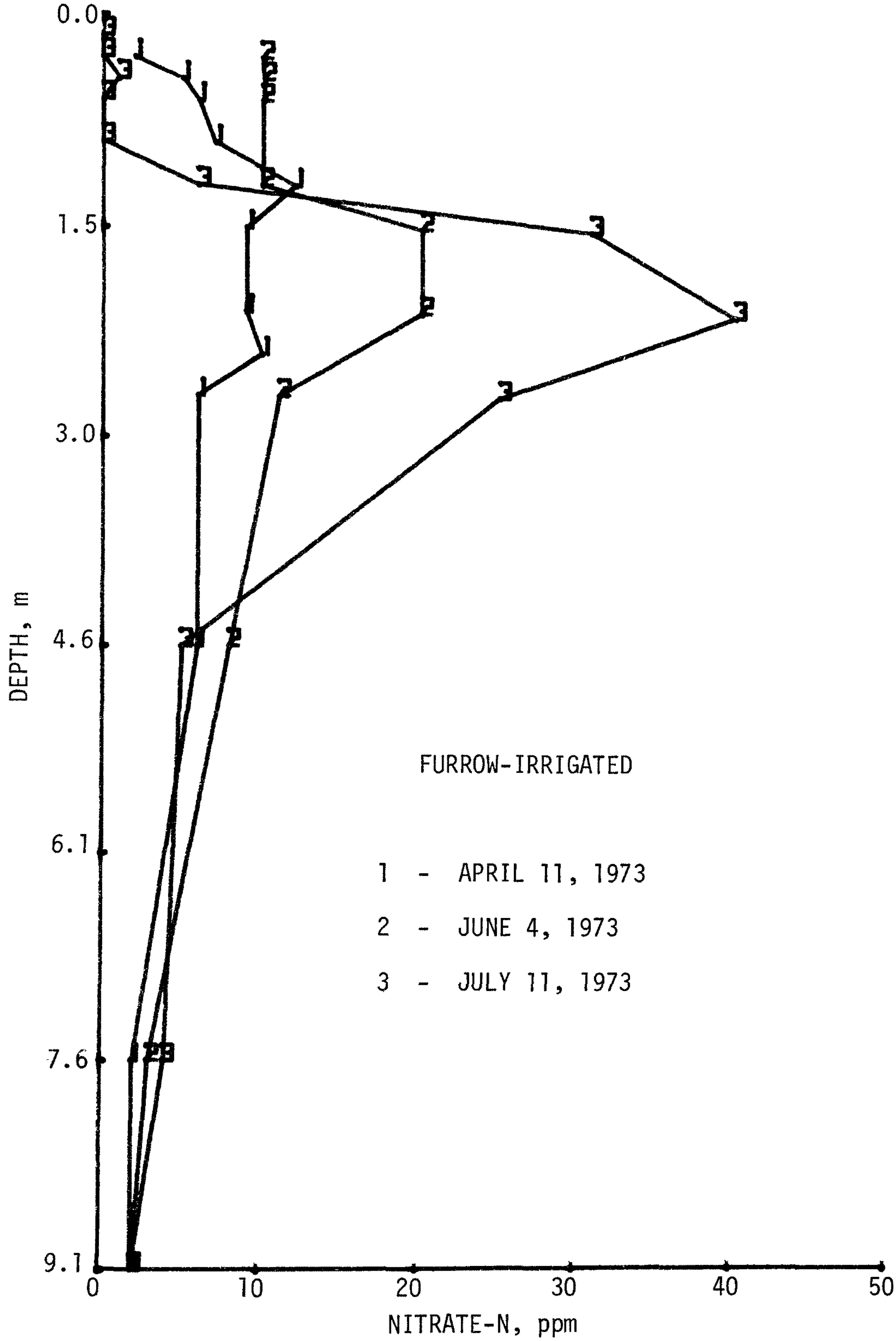


Figure 91. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a control plot.

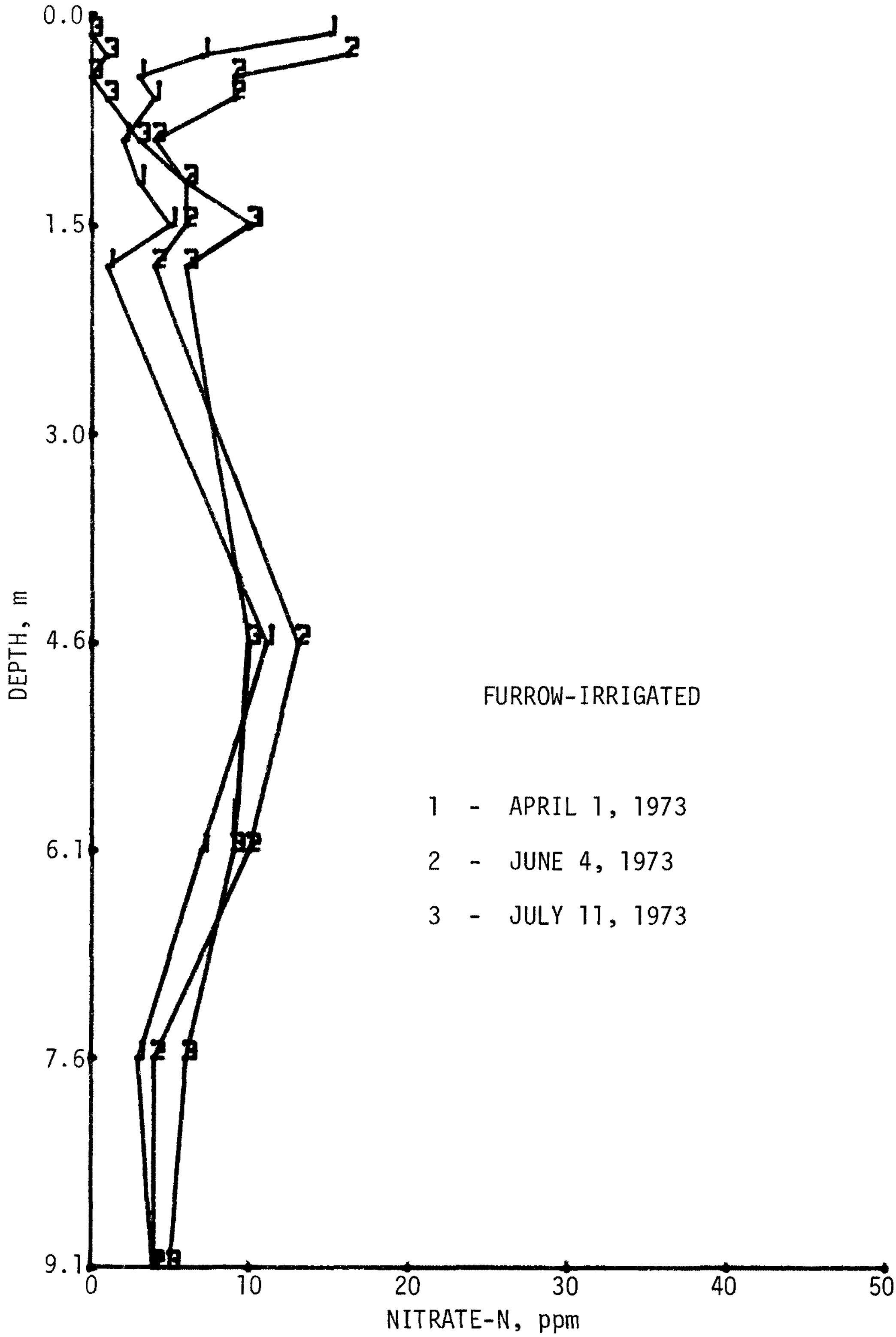


Figure 92. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a control plot.

increased from 10 ppm to 45 ppm at 2.1 m. The increases were not as dramatic in the other furrow-irrigated plot (Figure 92). However, there was an increase in nitrate-N from 1.2 to 1.8 m. No major changes in nitrate-N concentrations were noted below 4.5 m during 1973.

In general, there was an increase in the nitrate-N content of porous bulb extracts in the sprinkler-irrigated plots (Figure 93) and furrow-irrigated plots (Figures 94 and 95) below 1.5 m between 1971 and 1973. In the sprinkler-irrigated plot (Figure 93), the nitrate-N increased from 3 to 30 ppm between the end of the 1971 and 1973 growing seasons. In one of the furrow-irrigated control plots (Figure 94), the major increase in nitrate-N of the soil-water extracts occurred between 1.2 and 3.0 m between 1971 and 1973. In the other furrow-irrigated plot (Figure 95), the increases were between 4.6 and 7.1 m.

As can be seen in Figures 93, 94, and 95, there was considerable variability among the three plots in clay content at the various depths. It is notable that the higher nitrate-N values occurred in or just above zones of higher clay content.

In summary, relatively large increases in nitrate-N concentrations were found in porous bulb extracts from control plots between 1971 and 1973. This finding made it difficult to determine the separate contributions of soil nitrogen and fertilizer nitrogen. Consequently, a study in which the fertilizer was tagged with ^{15}N was initiated in 1973 to delineate the separate contributions and will be reported in another section. The increases noted between 1971 and 1973 indicate the possibility of a contribution of nitrate-N from soil nitrogen in unfertilized plots to irrigation return flow. The movement of this nitrogen was apparently influenced by the textural characteristics of the soil profile.

All irrigation in the Knox County area is currently by furrow or sprinkler irrigation systems. Most of the nitrogen fertilizer is applied in bands below the water furrow either as ammonia or Uran. Discussion relative to the current methods of applying various nitrogen sources in furrow irrigation systems follows.

Ammonia Banded Below the Level of the Water Furrow--

Where ammonia was applied (Figure 96) in 1973, there was little change in nitrate-N concentrations below 1.5 m except at 3.0 m. With the exception of this depth, the data obtained were similar to those obtained from the adjacent unfertilized plot (Figure 92). As would be expected, there was more nitrate-N in the surface 1.5 m in the plot fertilized with ammonia (Figure 96) than in the unfertilized plot (Figure 92). For the three-year period, the nitrate-N in the soil-water extracts in the unfertilized plots (Figure 95) and plots fertilized with ammonia (Figure 97) was similar below 3 m. This is further emphasized in a comparison of the nitrate-N content of porous bulb samples obtained from a control and ammonia-treated plot on July 2 (Figure 98). The data indicate that little nitrate-N was contributed to irrigation return flow from ammonia applied below the level of the water furrow.

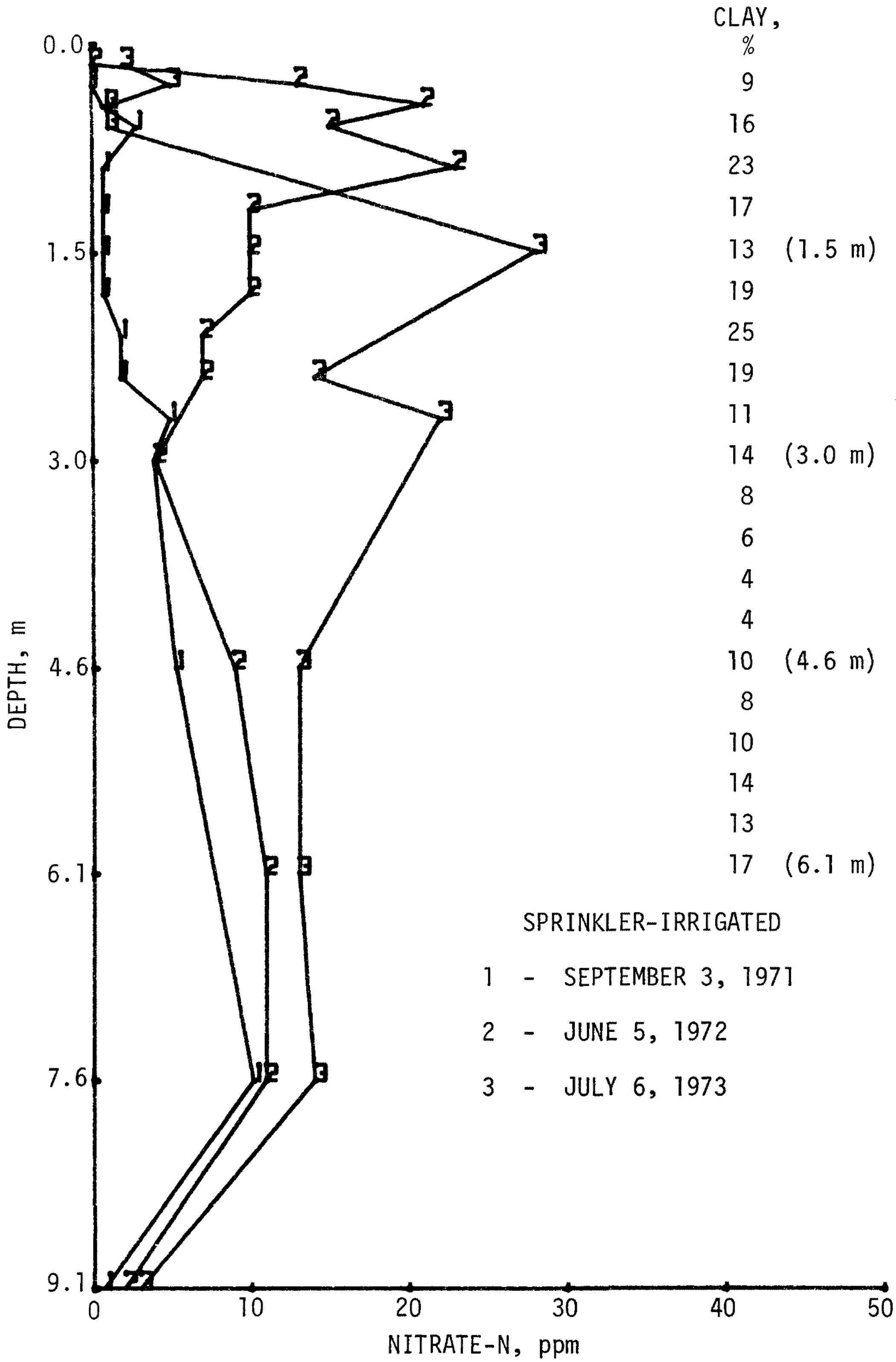


Figure 93. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a control plot.

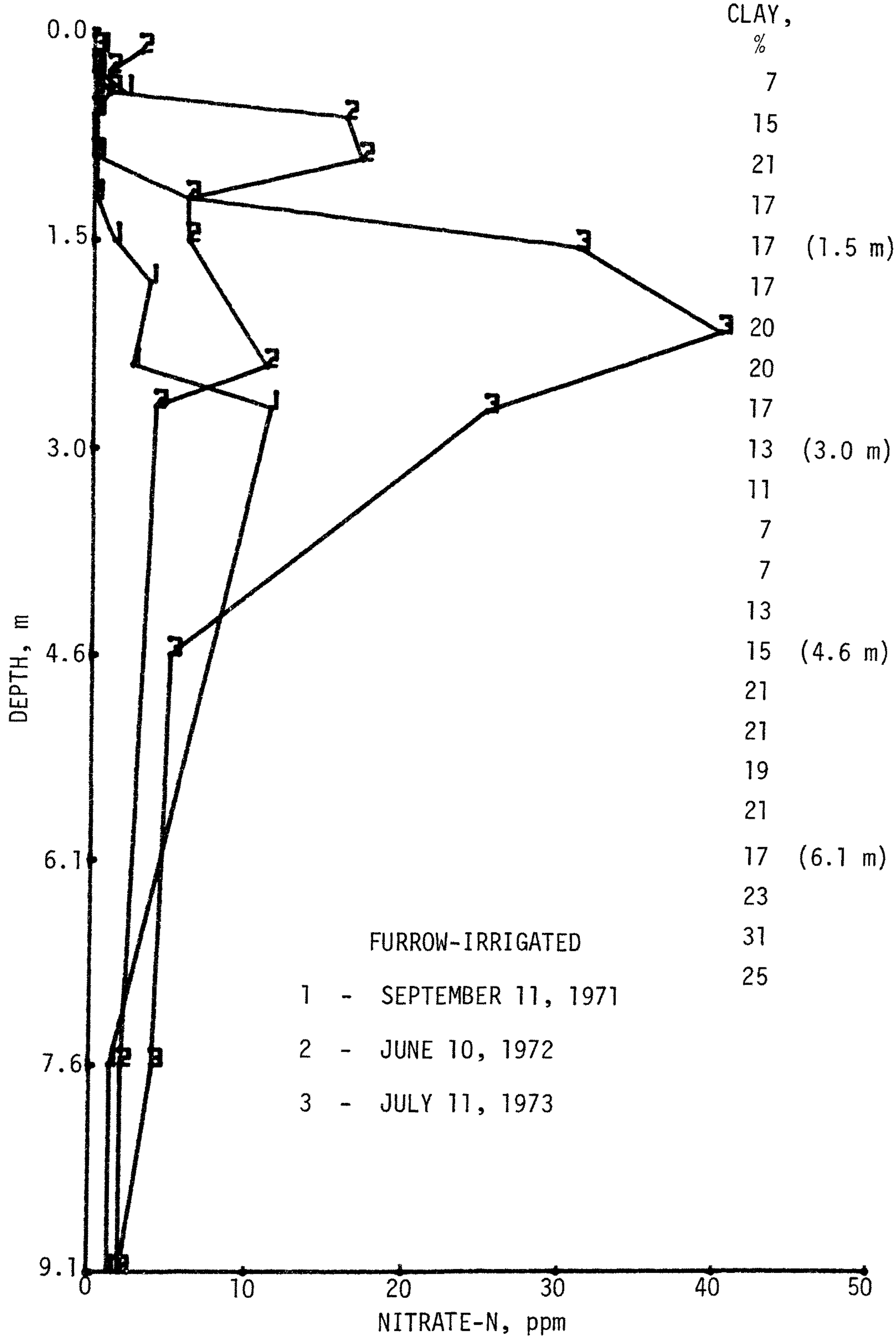


Figure 94. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a control plot.

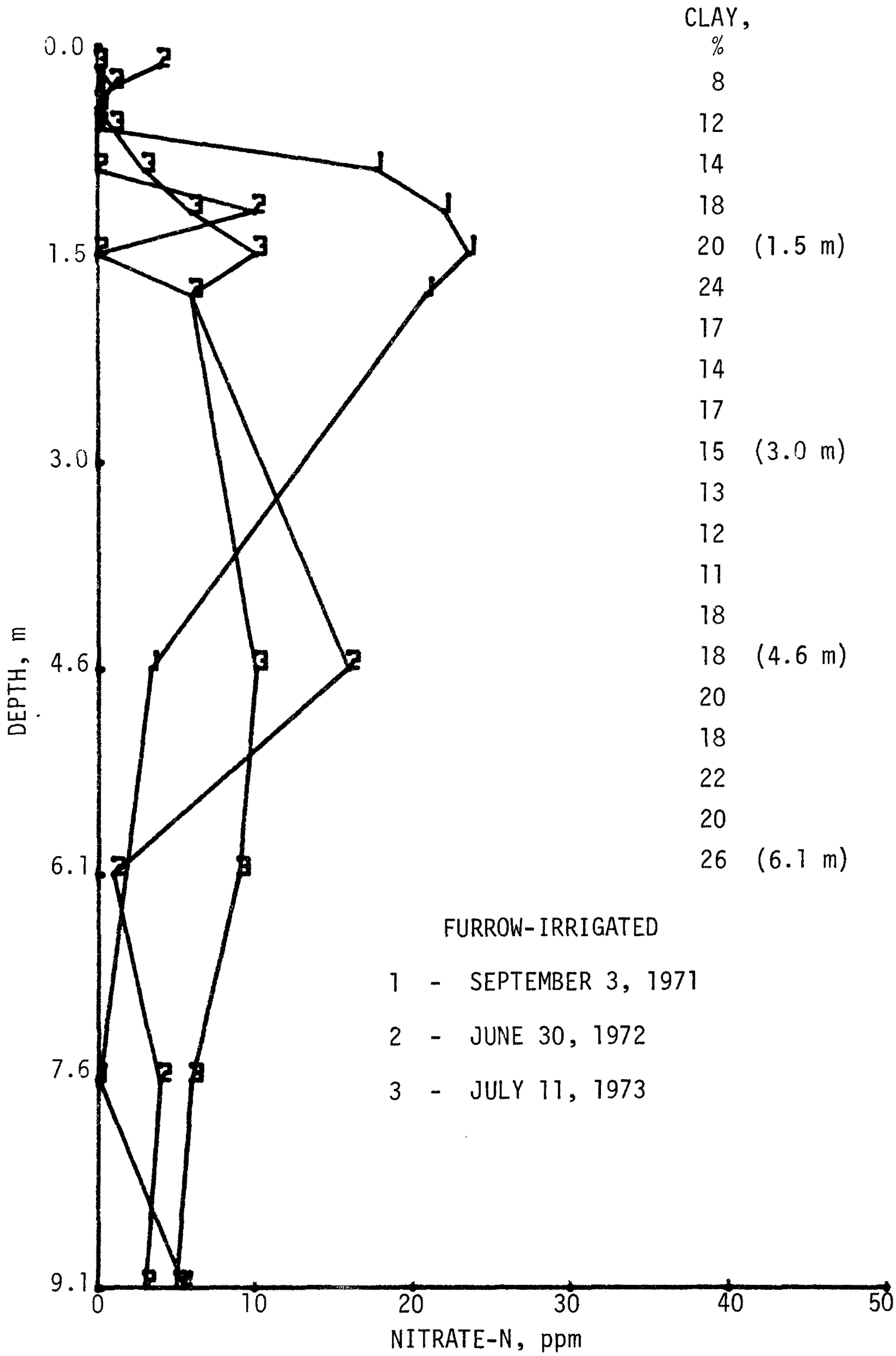


Figure 95. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a control plot.

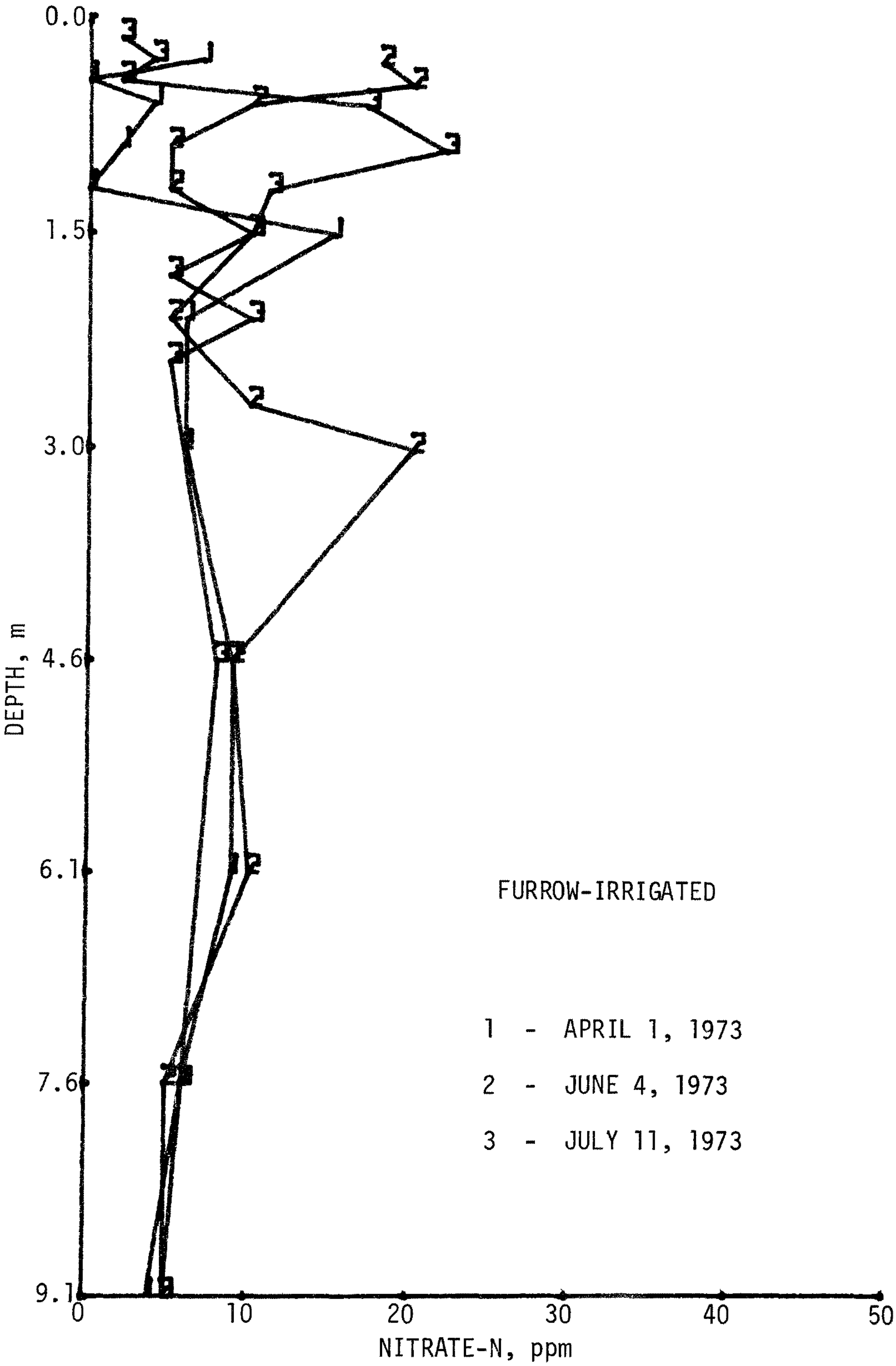


Figure 96. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a plot treated with anhydrous ammonia banded below the level of the water furrow.

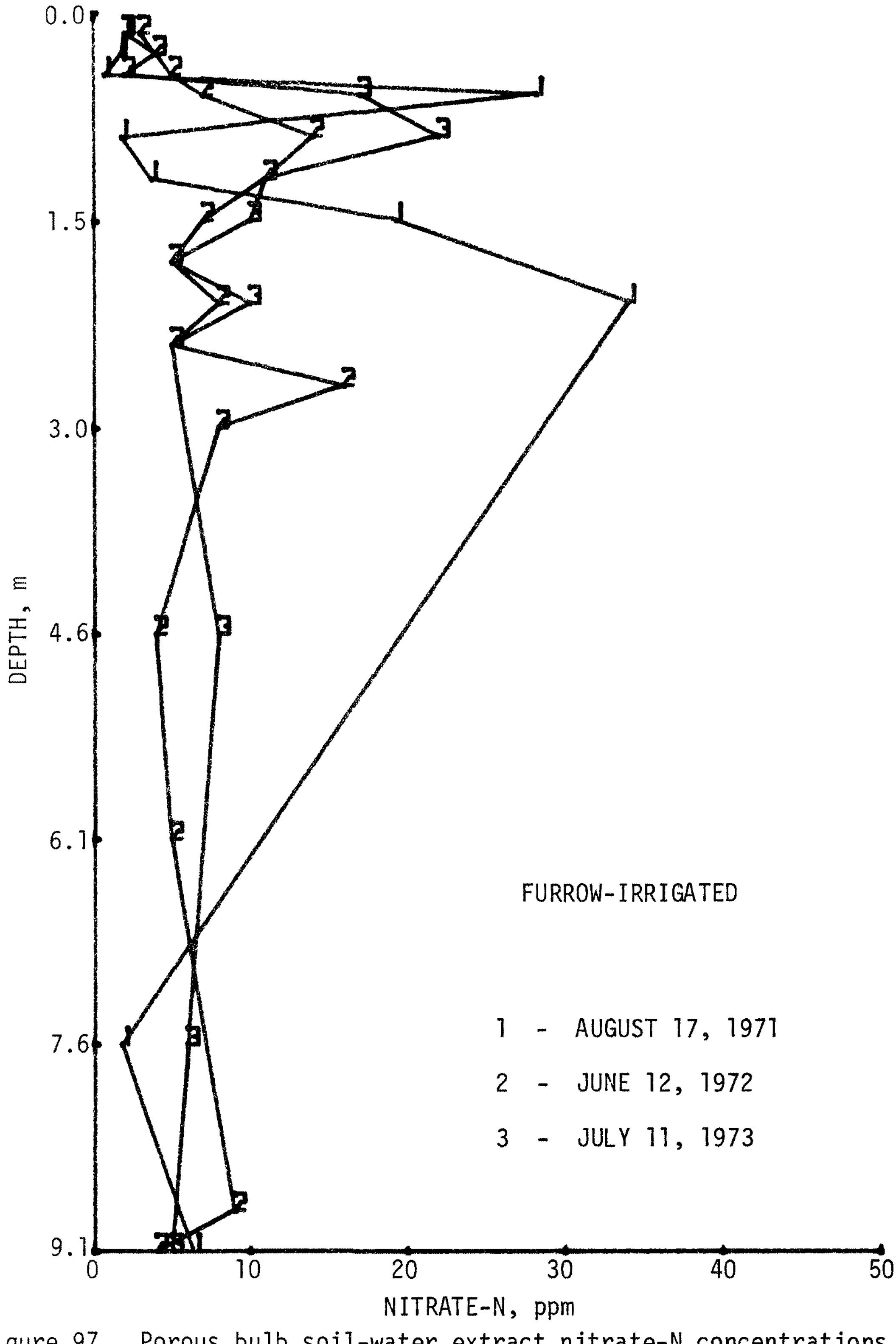


Figure 97. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with anhydrous ammonia banded below the level of the water furrow.

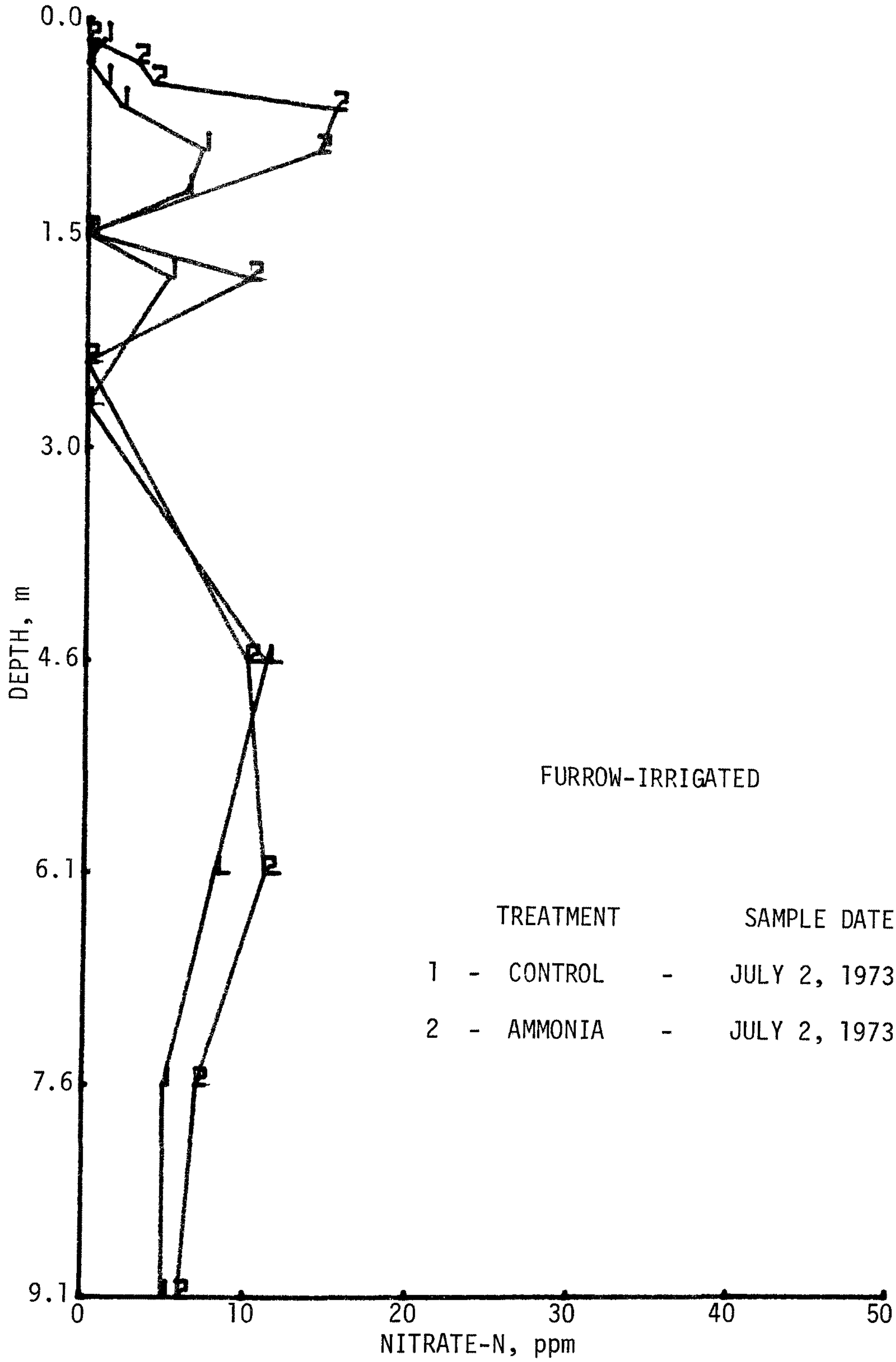


Figure 98. Porous bulb soil-water extract nitrate-N concentrations by soil depth for a control plot and plot with anhydrous ammonia banded in the bed below the bottom of the water furrow, 1973. (Total N - 374 kg/ha).

Uran Banded Below the Level of the Water Furrow--

The nitrate-N concentration of the soil-water extracts where Uran was banded below the level of the water furrow under furrow irrigation systems (Figures 99 and 100) was considerably higher than extracts from the unfertilized plot (Figures 92 and 95), especially below the root zone. Figure 99 shows the increase as the season progressed in 1973. At the beginning of the season on April 1, nitrate-N values down to 3.0 m were low. On June 4, high values for nitrate-N were noted in the surface 0.6 m due to the addition of fertilizer. With the exception of 4.6 m, increases in nitrate-N were noted from 1.5 to 9.1 m on July 11, 1973. All values for nitrate-N in the plot where Uran was banded below the level of the water furrow (Figure 99) were significantly higher than those obtained for the unfertilized plots (Figure 92).

Increases in the nitrate-N in the soil-water extracts were also noted to have occurred at depths from 2.7 to 7.6 m between 1971 and 1973 in the plot in which Uran was banded (Figure 100). The values were significantly higher than those in an adjacent unfertilized plot (Figure 95). A dramatic difference between the controls and the plot where Uran was banded can be seen where the two treatments are compared on the same graph (Figure 101). It thus appears that Uran banded below the level of the water furrow (Figure 100) has more potential to add nitrate-N to irrigation return flow than no fertilization (Figure 95) or ammonia applied below the level of the water furrow (Figure 97).

Uran Applied in the Irrigation Water--

Since Uran is commonly applied in the irrigation water in both furrow and sprinkler irrigation systems, such a treatment was included in this study. Figure 102 shows the data obtained during 1973 from furrow-irrigated plots. It can be seen that the nitrate-N values were higher than those of the unfertilized plot (Figure 92) and the plots to which ammonia was banded (Figure 96) but lower than the plot in which Uran was banded (Figure 99). The same general trend was true between 1971 and 1973 (Figure 103). The significantly higher concentration of nitrate-N of the plot where Uran was applied in the irrigation water over the control can be seen in Figure 104.

Values of 60- to 70-ppm nitrate-N in the soil-water extracts were also obtained during 1973 at 0.6 and 3 m, respectively, where Uran was applied through the sprinkler irrigation system (Figure 105). These high values were noted on both June 4 and July 10 and exceeded the values obtained from the control plots on the same date (Figure 90). There was also a major increase between 1971 and 1973 in the sprinkler-irrigated plot where Uran was applied in the irrigation water (Figure 106) which was also higher than the unfertilized plot (Figure 93). A direct comparison between the control plot and plot where Uran was applied in the irrigation water (Figure 107) on June 26 shows that the nitrate-N content of the fertilized plots was significantly higher below 3 m.

In summary, the data obtained between 1971 and 1973 showed much greater increases in nitrate-N concentrations in porous bulb soil-water extracts where Uran was used (Figures 99, 102, and 106) than where ammonia was applied (Figure 97) or the plots that were not fertilized (Figures 93 and 95).

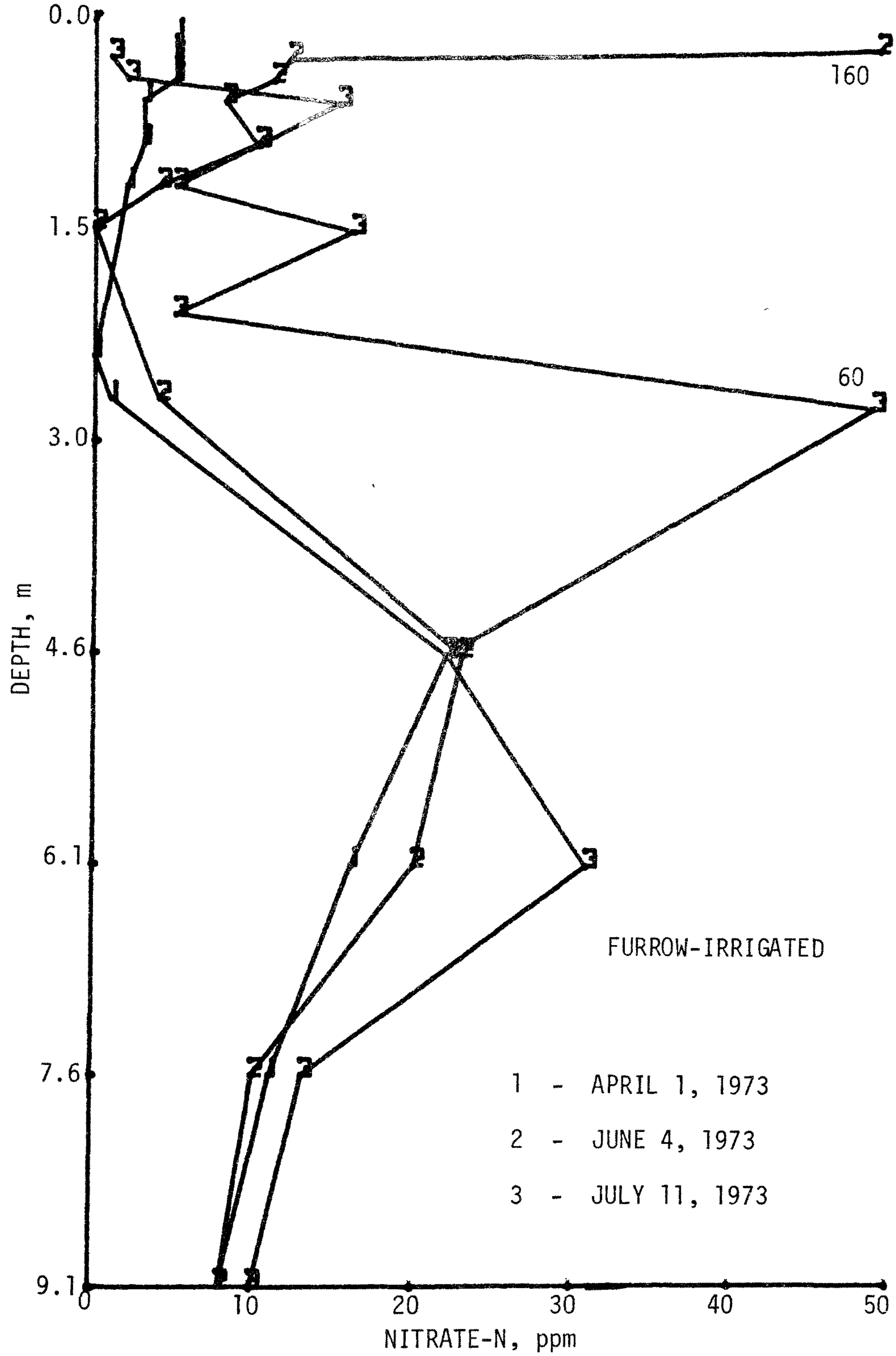


Figure 99. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a plot treated with Uran banded below the level of the water furrow.

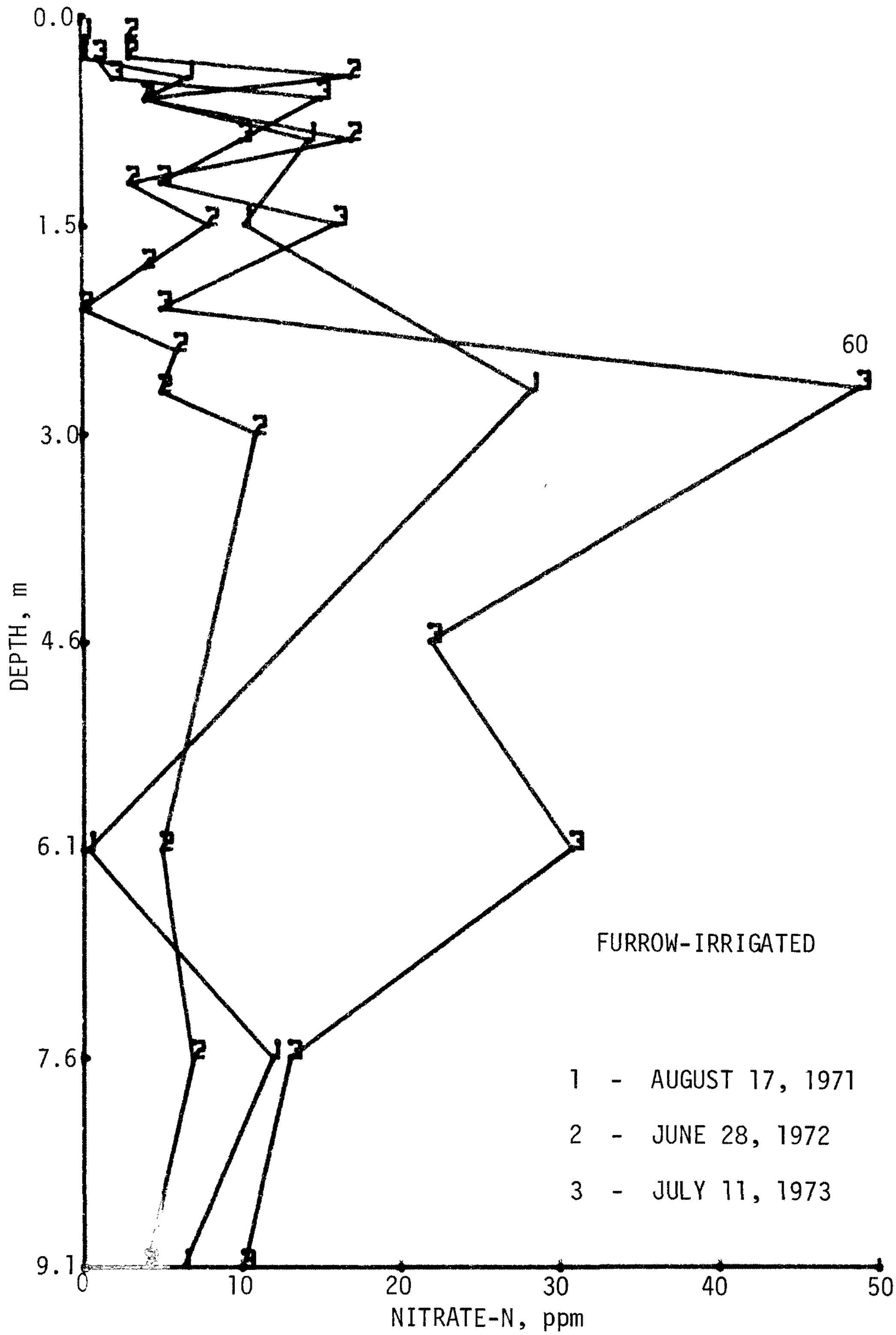


Figure 100. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with Uran banded below the level of the water furrow.

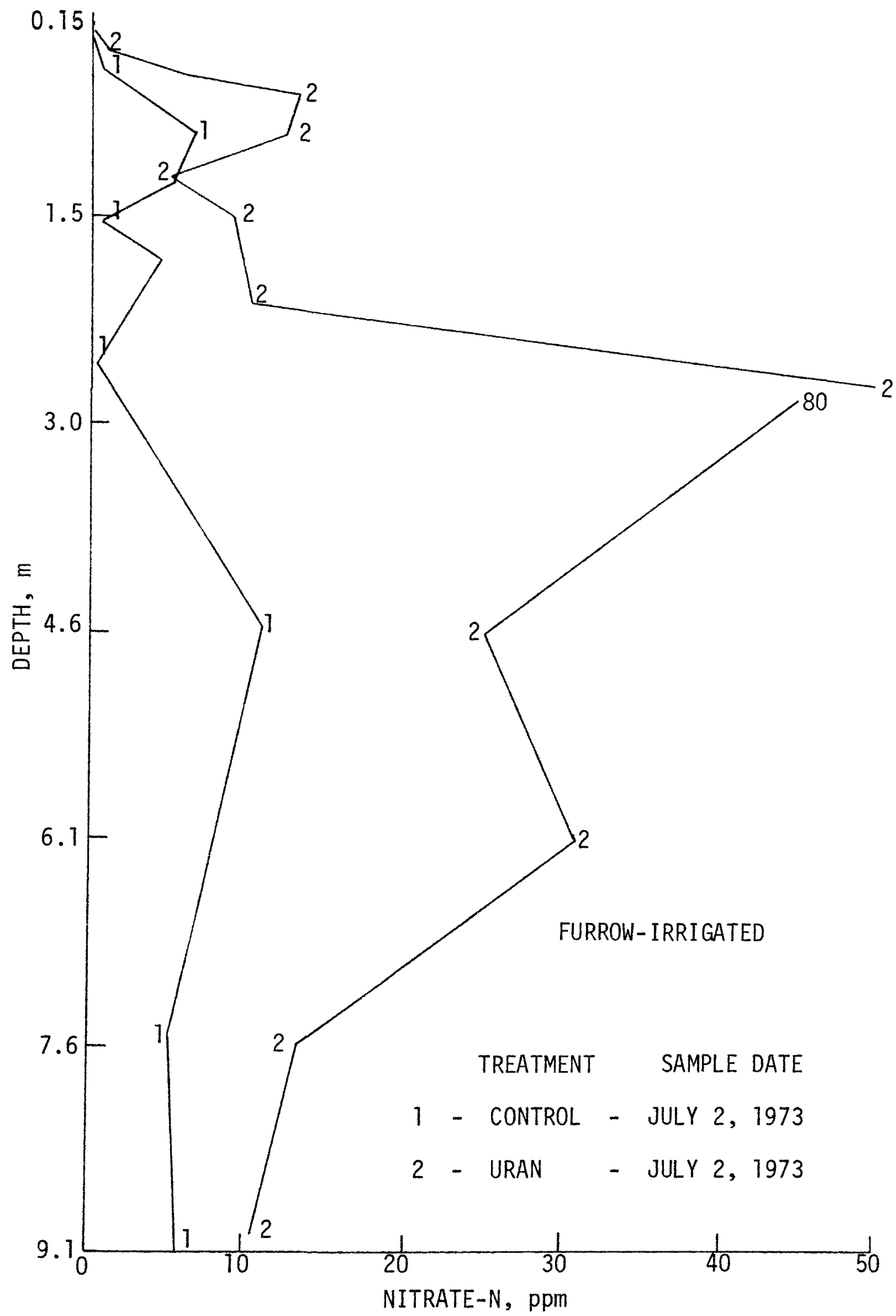


Figure 101. Porous bulb soil-water extract nitrate-N concentrations by soil depth for a control plot and plot treated with Uran banded in the bed below the bottom of the water furrow, 1973. (Total N - 368 kg/ha)

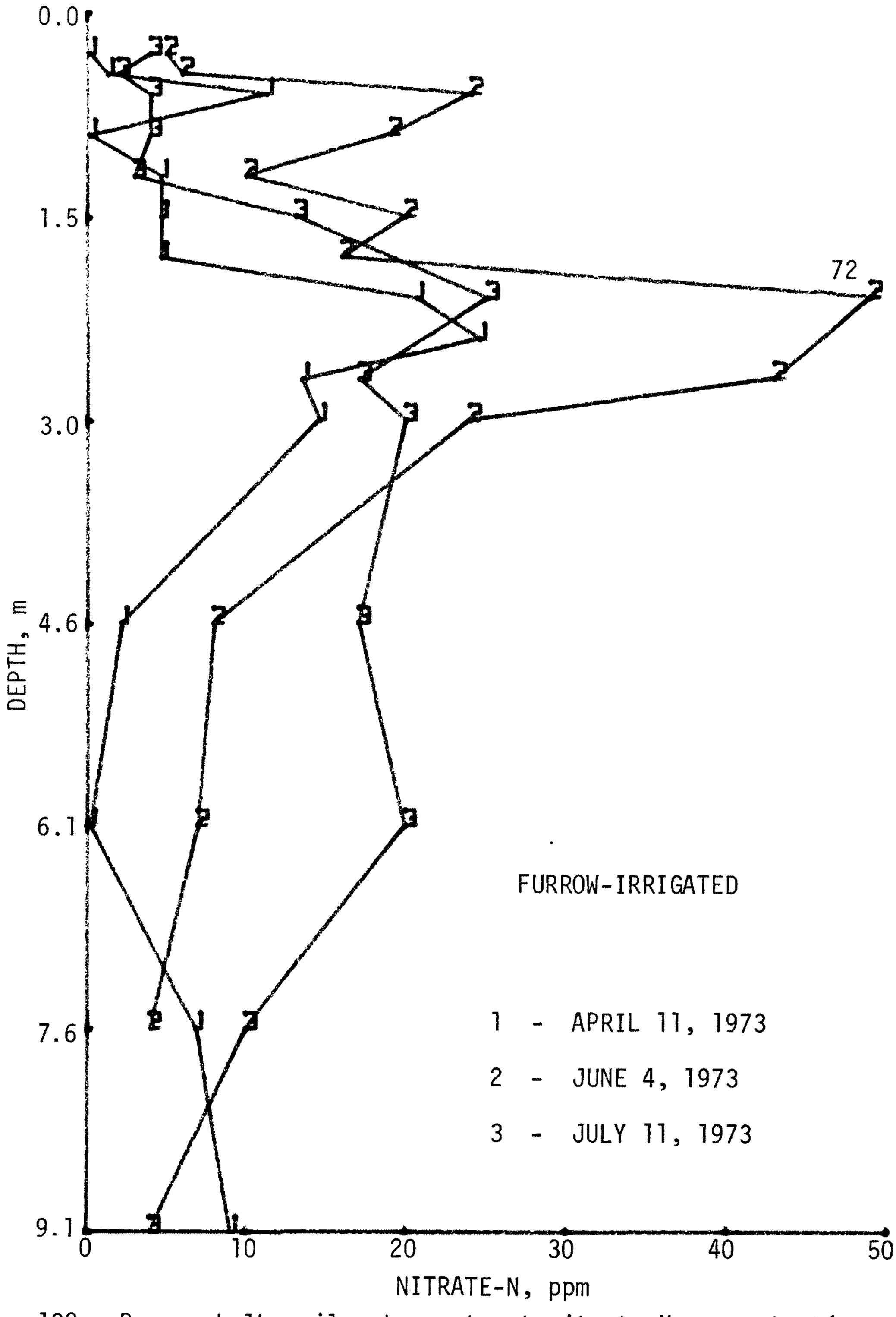


Figure 102. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a plot treated with Uran applied in the irrigation water.

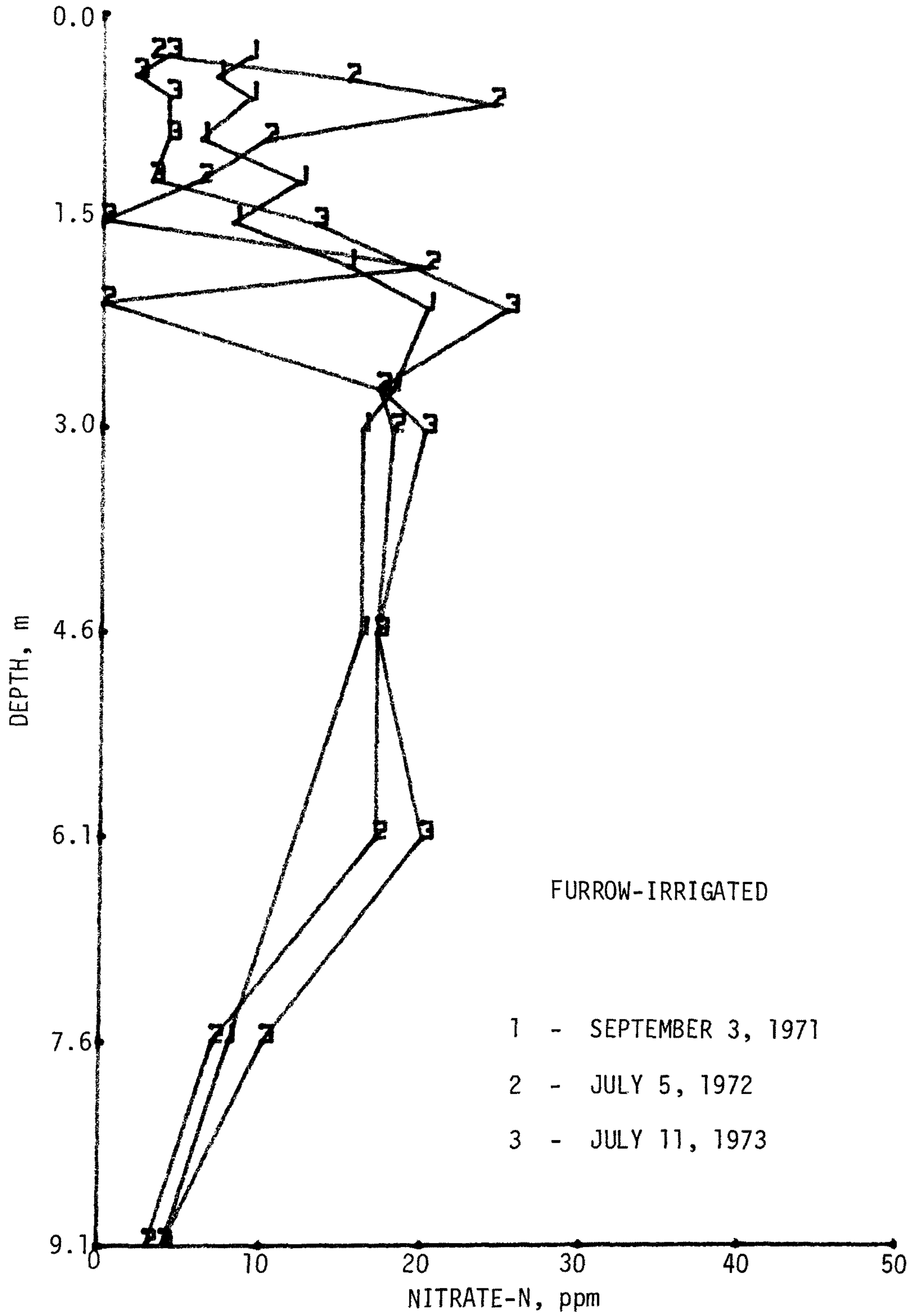


Figure 103. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with Uran applied in the irrigation water.

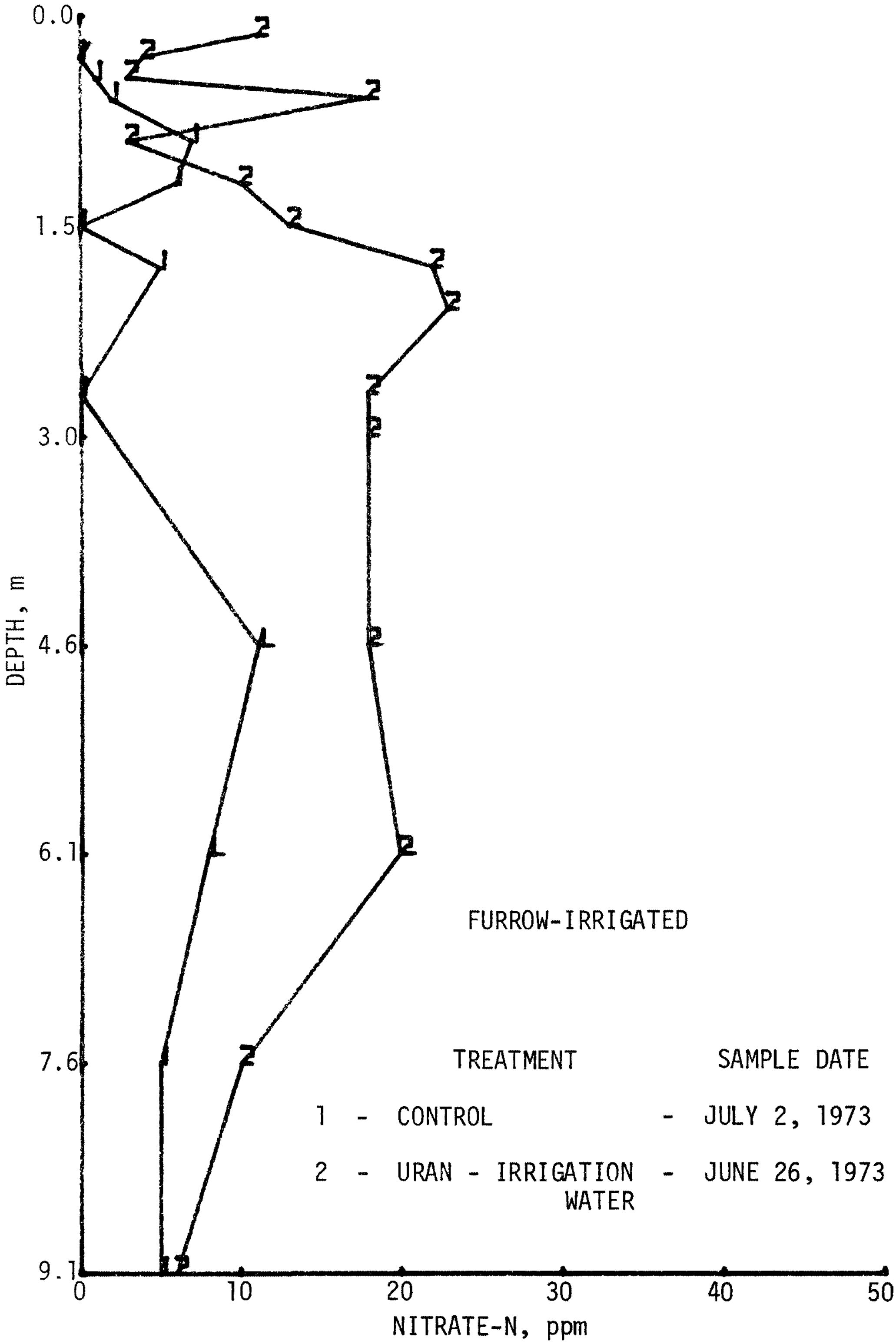


Figure 104. Porous bulb soil-water extract nitrate-N concentrations by soil depth for a control plot and a plot treated with Uran for three years, 1973. (Total N - 375 kg/ha)

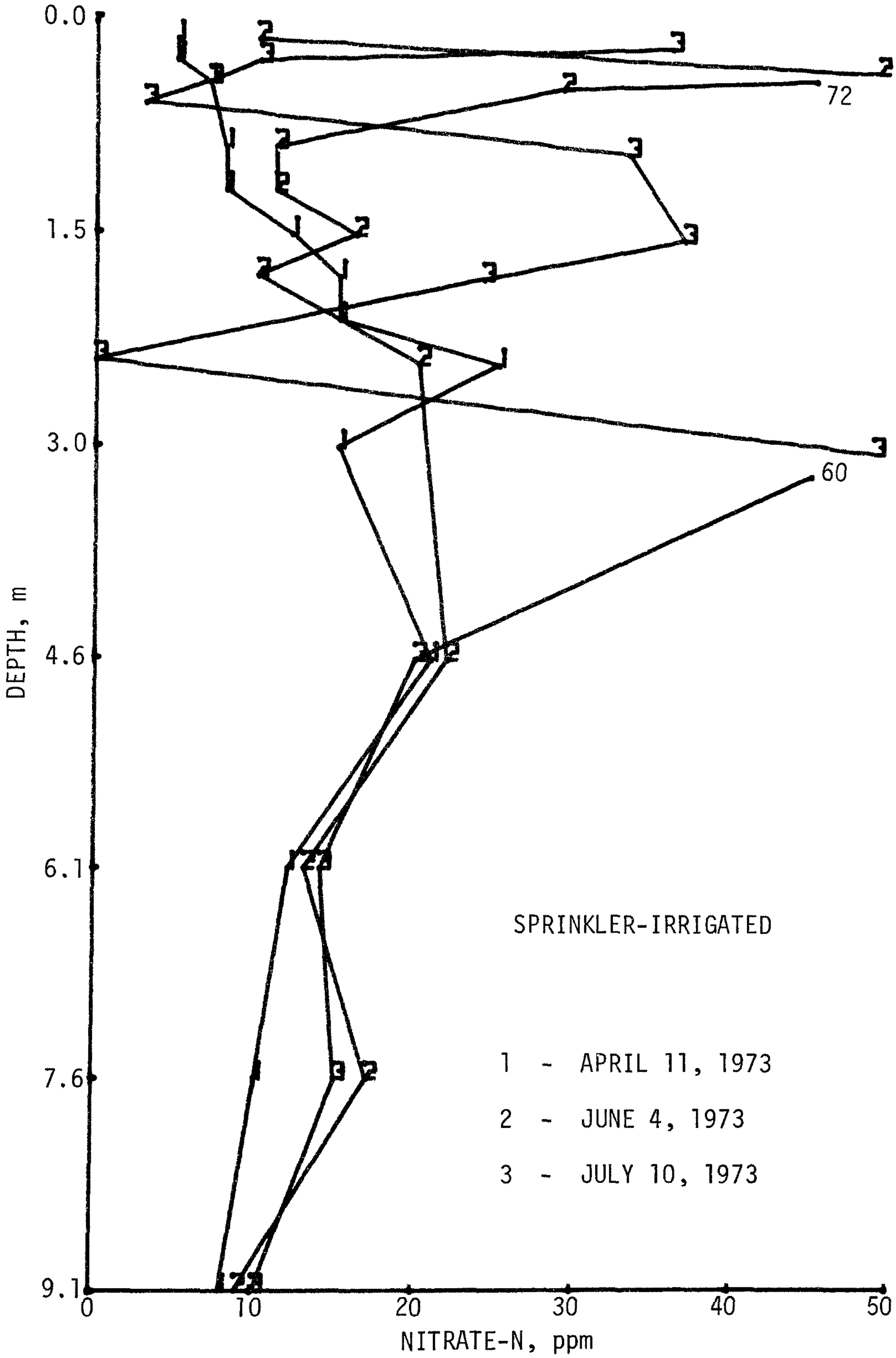


Figure 105. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a plot treated with Uran applied in the irrigation water.

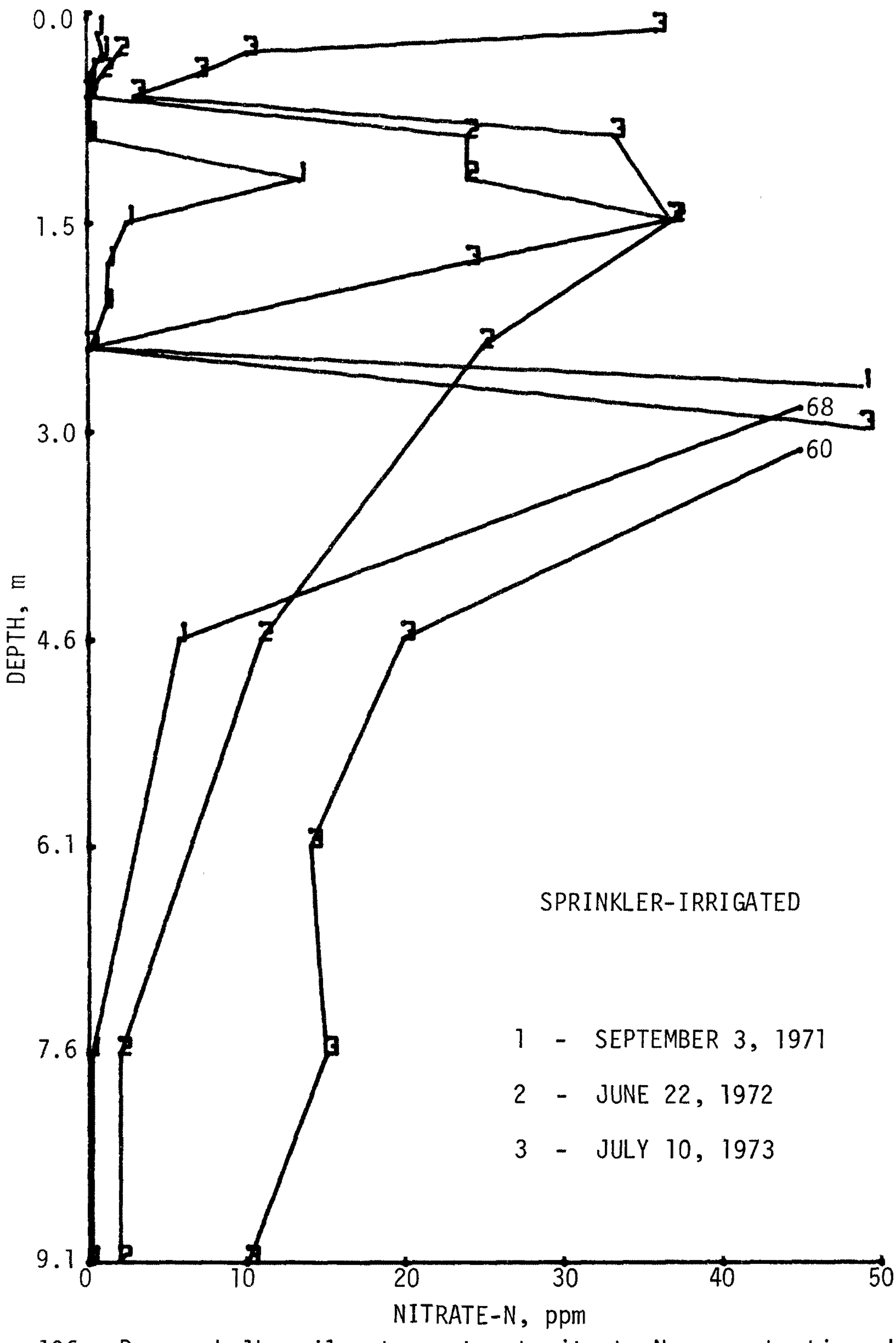


Figure 106. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with Uran applied in the irrigation water.

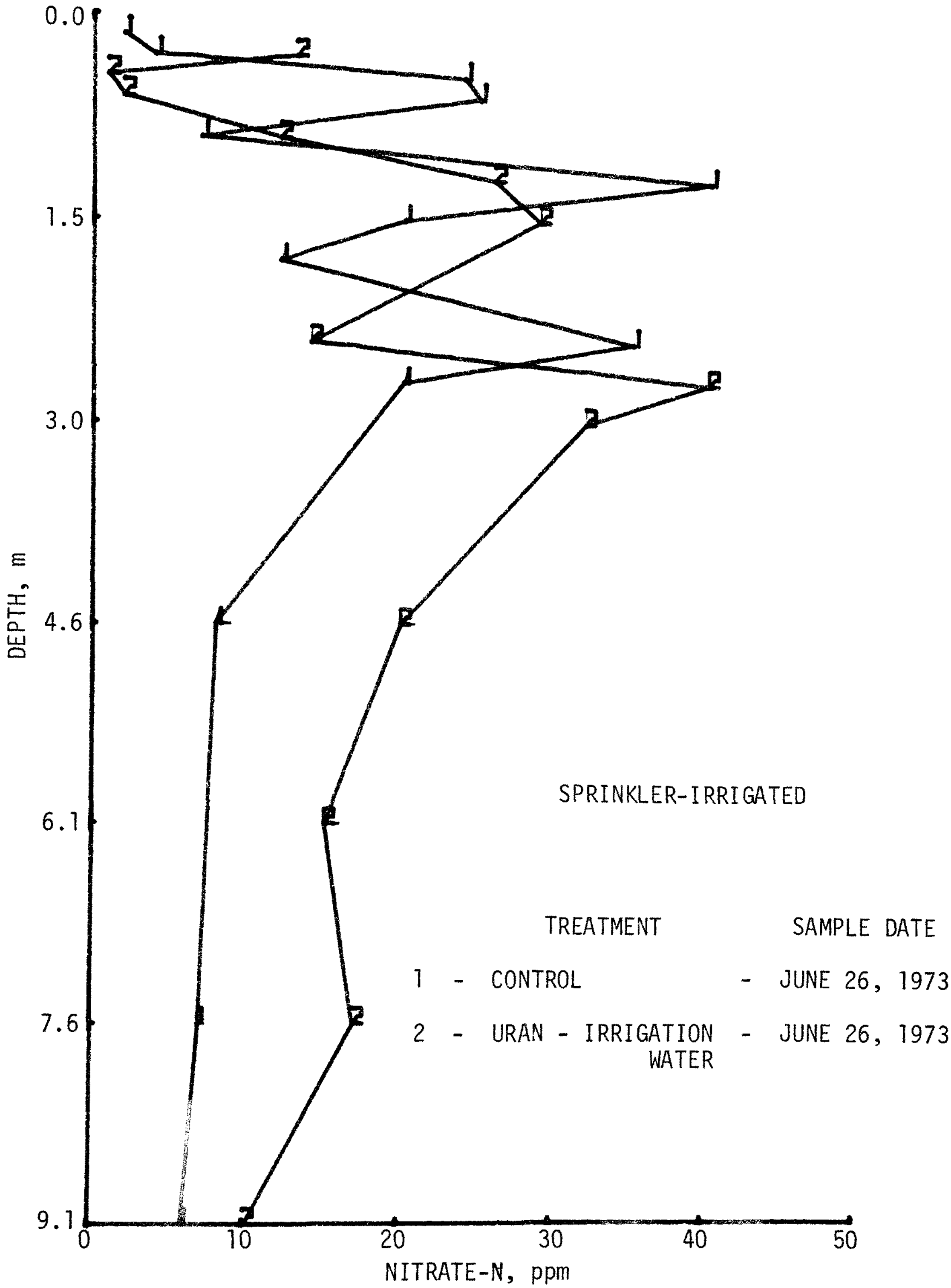


Figure 107. Porous bulb soil-water extract nitrate-N concentrations by soil depth for a control plot and a plot treated with Uran for three years, 1973. (Total N - 364 kg/ha)

Highest increases in nitrate-N below the root zone (>1.5 m) between 1971 and 1973 occurred in the furrow-irrigated plot where the Uran was banded below the level of the water furrow (Figure 100) and in the sprinkler-irrigated plot when it was applied in the irrigation water. A comparison of the clay content with the peak nitrate-N of the soil-water extracts indicates that peak nitrate-N concentrations occurred in or above the zones of highest clay content. The high nitrate-N concentration of the unfertilized plots (Figures 90 through 95) shows the problems of delineating the separate contributions of soil nitrogen and fertilizer nitrogen to irrigation return flow and necessitated the addition of a study in which the fertilizer was tagged with ^{15}N to determine the separate contributions of the two components.

These foregoing data show conclusively that some fertilizer nitrogen apparently was moving toward the water table below the root zone; however, it should be pointed out that these samples were taken from point sources in the profile and from the standpoint of total movement of nitrate to the water table would represent more of a qualitative than a quantitative measurement.

This can more clearly be seen in Figures 108 and 109. These data were obtained from soil samples taken at five equidistant locations laterally across the bed and down to a depth of 5.5 m. The samples were taken in 30-cm increments and a 1:1 sodium sulfate extract made and nitrate determined. The data in Figure 108 compares the extracts obtained at the beginning of the study in 1971 with those obtained from soil samples taken in August of 1974 from sprinkler-irrigated plots to which 508 and 514 kg of N/ha had been banded in the form of Uran and ammonia, respectively. It can readily be seen that when based on soil extracts the high nitrate-N concentration peaks did not occur but rather that the nitrate-N while increasing from 1971 to 1974 was more evenly distributed throughout the profile than indicated from the porous bulb extracts. The concentration levels, while increasing to some extent, still remained relatively low. Consequently, while it is evident that fertilizer nitrogen was contributing to an increase in nitrate-N in the irrigation return flow for currently-used sprinkler irrigation and fertilization practices, this contribution based on these data would appear to be relatively low.

Similarly, the data in Figure 109 for a furrow-irrigated plot, to which ammonia was banded using current fertilization practices, show an increase in nitrogen extractable from the soil in the nitrate form above that obtained from similar soil samples taken in 1971. Again, as for the sprinkler irrigation system, while there is an increase in nitrogen concentration, this increase seems to be rather low when put on a soil basis. The depth of the increase above the 1971 samples was not quite as great as that of the sprinkler system, as shown in Figure 108. Therefore, while it is evident that some increase in nitrate-N occurred in the soil profile, these increases would appear to be relatively small.

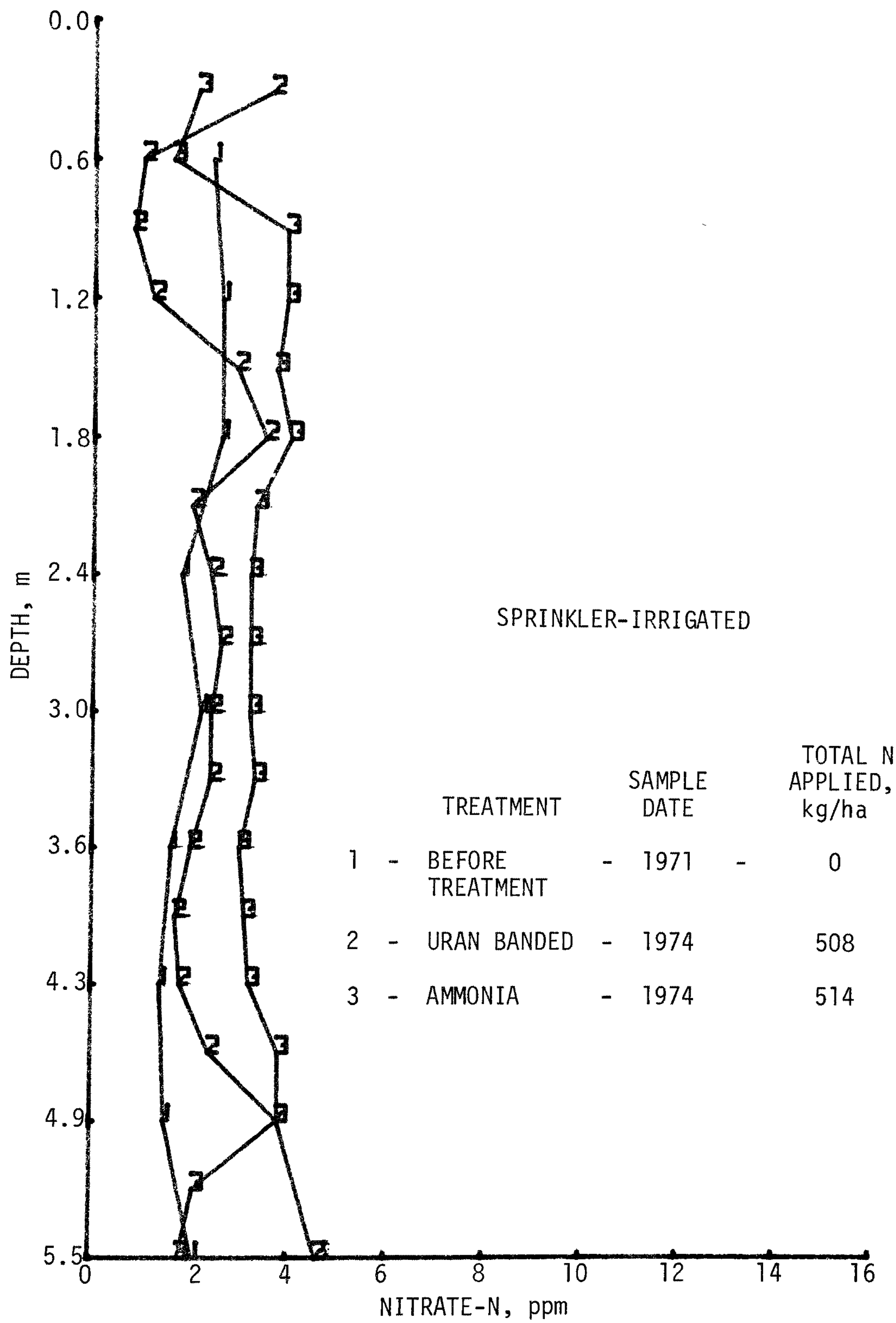


Figure 108. Soil extract (1:1) nitrate-N concentrations by soil depth before treatment (1971) and after four years of N application, 1974.

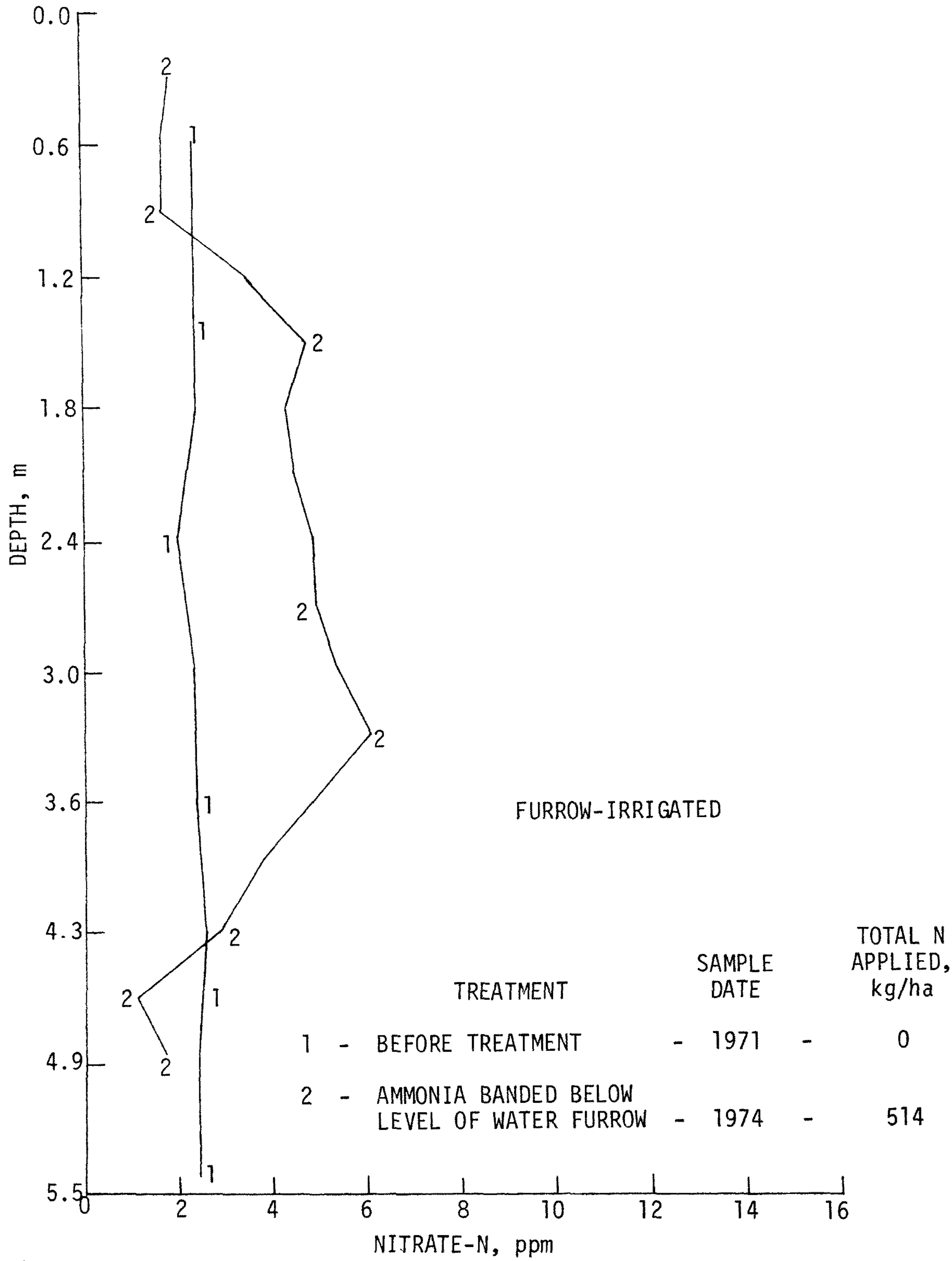


Figure 109. Soil extract (1:1) nitrate-N concentrations by soil depth before treatment (1971) and after four years of N application, 1974.

Model for Leaching of Nitrate From Warm Sandy Soils

Due to the variability in the soils located at the site and the problems encountered with previously discussed analytical and statistical models, it was decided to develop an empirical model for nitrate movement using data from the site. A discussion of this development follows:

Basic Assumptions--

Nitrate was assumed to move with the soil water. Water movement was assumed to be one-dimensional piston displacement. Availability of nitrate from organic material was limited by the rate of mineralization rather than nitrification. Denitrification was neglected. Temperature effects on nitrogen reactions were neglected. Plant uptake of nitrate-N was proportional to the nitrate concentration at a particular depth but was not influenced by location within the root zone. Water added in excess of field capacity drained rapidly through the soil profile. Evaporation was neglected. Other assumptions are implicit within the model functions.

Evaluation--

The model consists of equations describing the various physical processes. Constants in these equations were chosen by a procedure in which the sum of squares of differences between predicted and measured values of soil nitrate-N amounts was minimized. All constants were varied simultaneously to decrease that sum until an optimum combination was achieved.

Initial Conditions and Input Data--

Input data were obtained during an 87-day growing season in which sweet corn was grown in a loamy fine sand. Initial conditions include distribution of soil nitrate and soil water with depth. Initial conditions which were estimated by the optimization of model constants were amount and distribution of nitrogen available from the organic matter for mineralization and nitrification.

Input data with time include rainfall, irrigation, fertilization, potential ET, LAI, uptake of nitrogen by the crop, and the relationship for calculating transpiration from leaf area and potential ET. Input data which were estimated by the optimization of model constants include the relationship between the root-zone depth and crop age. The model could be modified slightly to consider incorporation of crop residues.

The Algebraic Model - Nitrogen Relations--

The top 150-cm thickness of the soil profile was divided into five 30-cm layers. Calculations of nitrogen reactions (and water movement) were made daily. The net rate of mineralization was assumed to be slower than the rate of nitrification. The rate of mineralization-nitrification (RMIN) in a soil layer was defined by the equation,

$$RMIN = A7(ARNV) + A8(CNO3) \qquad [12]$$

in which A7 and A8 are constants, ARNV is the amount of N available for mineralization and nitrification from organic residue in the layer, and

CNO3 is the amount of nitrate-N now present in the layer. Units of RMIN, ARNV, and CNO3 are kg N/ha per 30-cm layer.

The initial amount and distribution of residue N per cm, RNV, was obtained by optimizing the constants in the equation

$$RNV_D = RNV_{D=0}\ e^{A2(D)} \qquad [13]$$

in which A2 and $RNV_{D=0}$ are constants, and D is soil depth in cm. The units of $RNV_{D=0}$ and RNV are kg of available N per ha-cm.

The daily increase in nitrogen in the above ground portion of the crop (PLANT) had been measured. The total plant uptake of nitrate-N, PUP, kg NO3-N/ha per day was obtained by

$$PUP = A12(PLANT) \qquad [14]$$

in which A12 is an optimized constant.

The layers in the soil from which this nitrate-N was taken were determined from an equation relating root-zone depth in 30-cm layers (RZD) and plant age (DAY):

$$RZD = (A13)(DAY)^{A14} \qquad [15]$$

in which A13 and A14 are constants which were optimized in the model evaluation. The value of RZD was rounded to the next highest integer. Nitrate extracted from a particular layer was assumed proportional to the amount of nitrate-N in that layer, that is nitrate-N in that layer was reduced by the equation

$$CNO3 = CNO3 - PUP(CNO3/SUCON) \qquad [16]$$

in which SUCON is the sum of the nitrate-N amounts in the root zone, RZD, and the other variables are as defined.

Nitrate-N amounts were as adjusted to account for mineralization-nitrification, RMIN from Equation 12,

$$CNO3 = CNO3 + RMIN \qquad [17]$$

Sodium nitrate fertilizer nitrogen was added to the top 30-cm layer.

The Algebraic Model - Water Relations--

For calculation of water movement, the soil was also divided into five 30-cm layers. The layers in the root zone, RZD, supplied water for transpiration. If the leaf area index was ≥3., transpiration was equal to potential evapotranspiration. For values of leaf area index ≤3., transpiration was calculated from the equation,

$$\text{TRANS} = \text{ETP}\left(\frac{\text{VLAI}}{3.}\right)^{0.6137} \quad [18]$$

in which TRANS is the transpiration in mm, ETP potential evapotranspiration in mm, calculated by the method of Jensen, et al. (10), and VLAI is the leaf area index.

Drainage from a layer in the soil profile was permitted when the water content exceeded the field capacity of the layer, A4. The units of A4 are mm of water per 30-cm layer. However, drainage was limited so that the vertical movement of N did not exceed 30 cm per day. Daily amounts of rain plus irrigation were added to the top 30-cm layer of soil.

Optimum Constants and Goodness of Fit--

Optimum values of the model constants are

$$
\begin{aligned}
\text{initial } RNV_{D=0} &= 11. \\
A2 &= -0.075 \\
A4 &= 62. \\
A7 &= 0.065 \\
A8 &= -0.012 \\
A12 &= 1.2 \\
A13 &= 1.6 \\
A14 &= 0.06
\end{aligned}
$$

Soil nitrate values were measured at two locations and four dates on Plot 6 during 1973. The top 150-cm layer of soil was divided into five 30-cm layers for measurement. The minimum sum of squares of differences between these 40 measured values and the corresponding 40 calculated values was 18,273 $[\text{kg/ha-30 cm}]^2$. The two locations were intended as replications. The sum of squares of differences between 20 comparable measured nitrogen amounts in each location was 10,540 $[\text{kg/ha-30 cm}]^2$. A graphical comparison of predicted and measured values is given in Figure 110. The model underestimated peak values on the first two sampling dates and overestimated peak values on the last two sampling dates.

Predicted Leachate Concentrations With Various Input Conditions--

Once the model constants were determined, the model was used to predict leachate concentrations occurring with the various combinations of input conditions shown in Table 21. Other data, rainfall, transpiration, potential plant uptake of N, etc., were the same as those used to seek model constants.

For the 528 combinations, amounts of water and nitrate-N leached past the 150-cm depth were calculated. Whenever leaching reduced nitrate amounts in the root zone below that needed to adequately supply the crop, the deficiency was noted. The sum of daily deficiencies was used to calculate a ratio of N supplied to plants to N needed by plants. The amount of nitrate-N remaining in the top 150-cm of soil at the end of the 90-day season was also computed. Average concentrations of nitrate-N in the leachate are shown in Figures 111 and 112 as a function of the ratio of

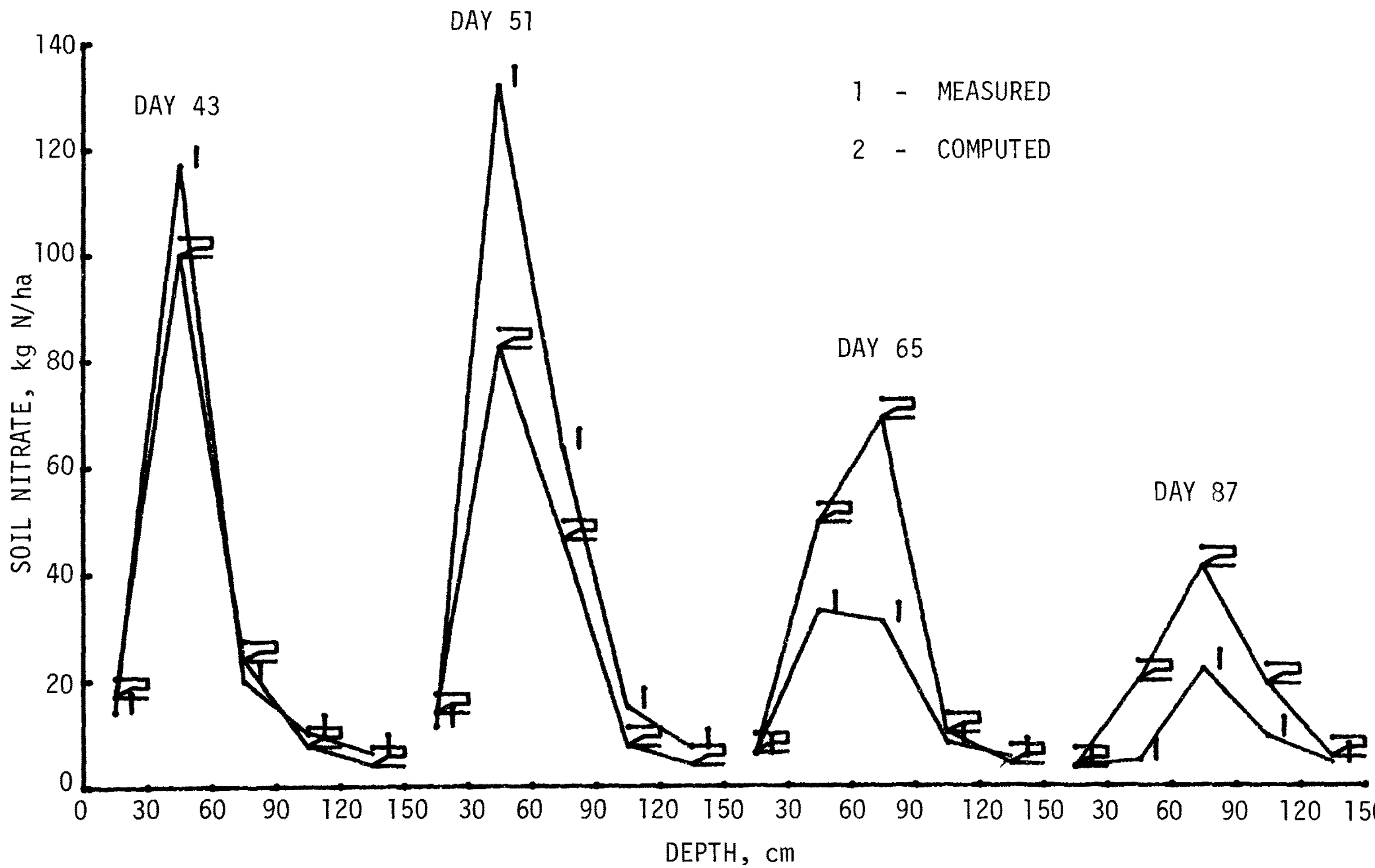


Figure 110. Comparison of predicted values of soil nitrate with measured values at a depth of 30 cm. Values plotted are the average of two locations.

TABLE 21. VARIOUS INPUT CONDITIONS MODELED

Available residue nitrogen		Fertilizer nitrogen,* kg/ha	Net ET† between irrigations, mm	Irrigation amounts divided by net ET since last irrigation
Surface cm, kg/ha-cm	Total profile, kg/ha			
0	0	0	20	1.0
10	133	100	40	1.2
20	267	200	60	1.4
30	400	300		1.6
				1.8
				2.0
				2.2
				2.4
				2.6
				2.8
				3.0

*One-fourth of the fertilizer was added at planting; three-fourths was sidedressed 30 days later. Fertilizer was assumed to be in the form of nitrate.
†Transpiration minus rainfall.

irrigation amounts to net ET. Minimum levels of nitrogen additions which were ample for plants are noted in Table 22. Leachate concentrations were low when excess water was not applied. The model was written in Fortran for the IBM 370 computer. Compile time averaged about 10 seconds. Computation time was slightly less than 0.38 seconds per 87-day season.

Conclusions--

The model presented is an approximate empirical model intended for use in determining relative effects. The two most important factors affecting leachate concentrations of nitrate-N during a single growing season are irrigation amounts and total nitrogen amounts. The source of nitrogen, fertilizer or residue, had little effect on concentration of nitrate-N in the leachate. When irrigation amounts were equal to the net ET, the amounts of N and water leached past the 150-cm depth were almost negligible (Table 22).

For the conditions modeled, maximum concentrations of nitrate-N in the leachate occurred when the ratio of irrigation amounts to net ET was about 2.4 (Figures 111 and 112) with large amounts of nitrate-N present. This condition could readily occur when furrow irrigation systems are used to irrigate shallow-rooted crops grown in sandy soils. In some areas with sandy soils, such as East Texas, the annual precipitation is about 2.5 times the net annual lake evaporation. In such areas it would be most important to limit the amount of nitrate-N in the root zone by small frequent applications of N or possibly by addition of slow-release fertilizers.

The hydraulic conductivity of the soil modeled is very small at soil-water potentials high enough to support most crops. Therefore, tensiometers

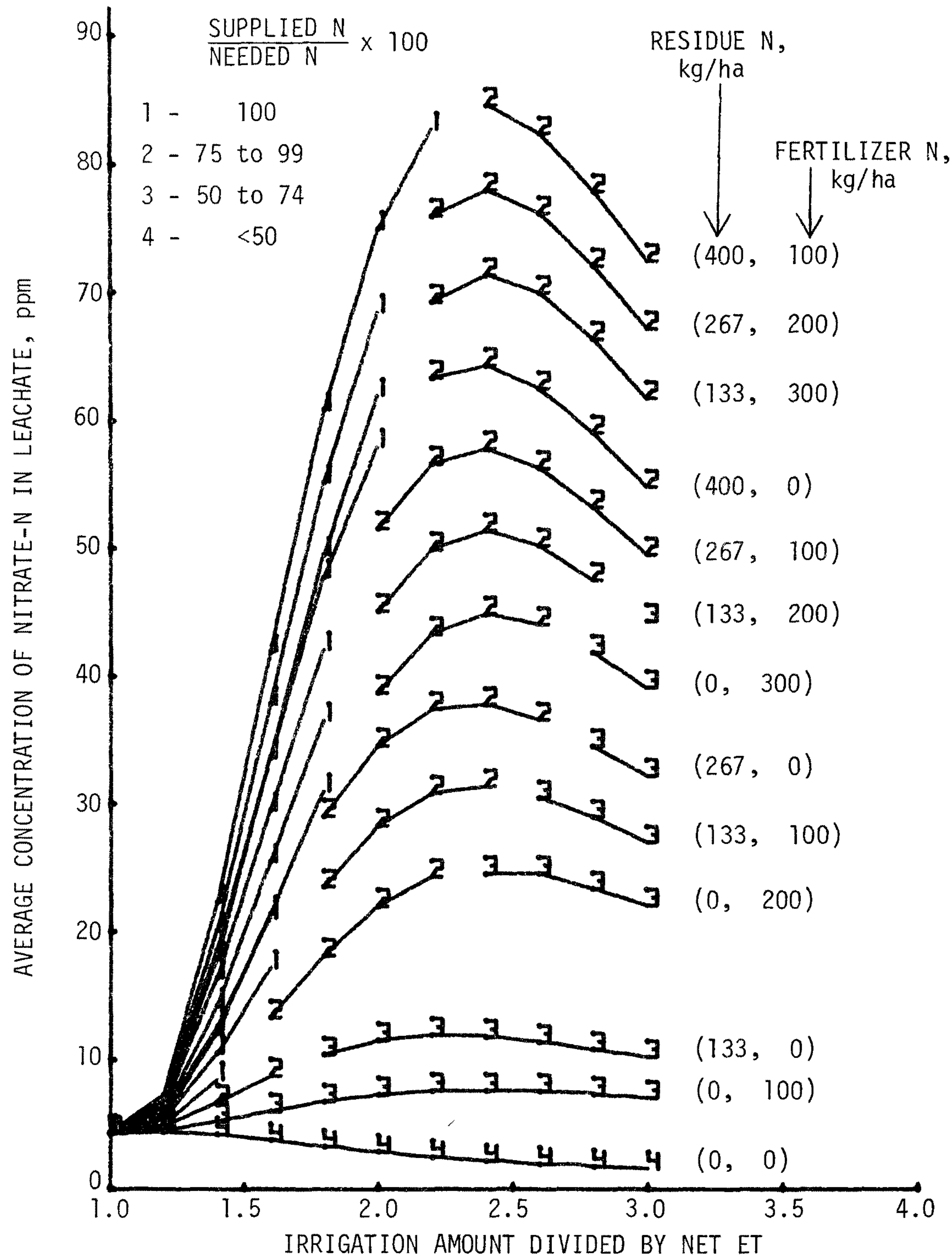


Figure 111. Relationship between leachate concentrations, excess water additions, and fertility levels. Irrigations were applied when the net evapotranspiration was 20 mm.

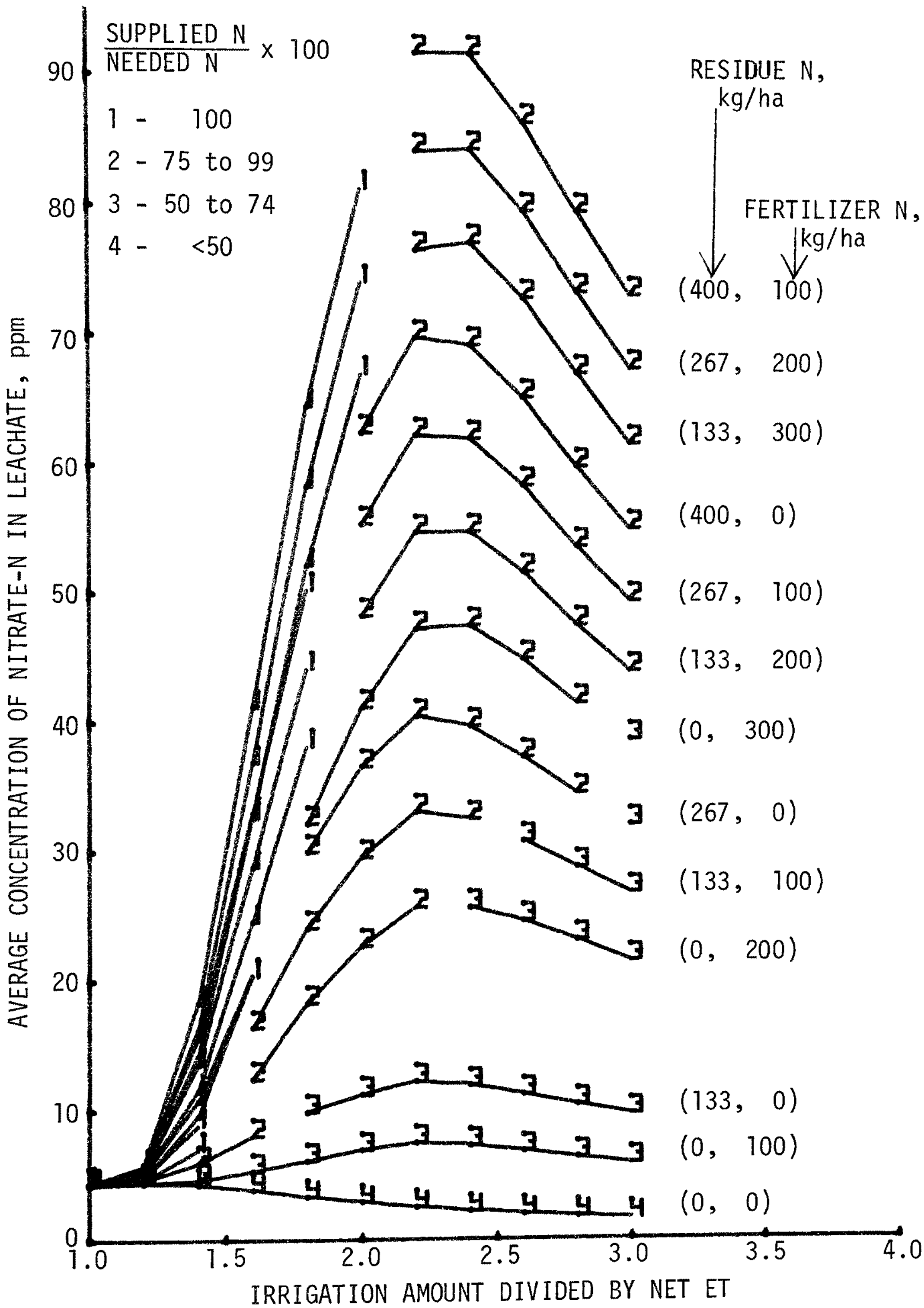


Figure 112. Relationship between leachate concentrations, excess water additions, and fertility levels. Irrigations were applied when the net evapotranspiration was 60 mm.

TABLE 22. MINIMUM LEVELS OF FERTILITY FOR AMPLE PLANT NITROGEN (PLANTS USED 164.35 KG OF NITROGEN PER HA)

Net ET at irrigation, mm	Residue nitrogen, fertilizer nitrogen, kg/ha	Ratio of irrigation to net ET	Concentration of nitrogen in leachate, ppm	Nitrate-N left in profile, kg/ha	Drainage, mm	Nitrate-N leached, kg/ha
20	(0, 200)	1.0	4.27	43.0	12.6	0.54
60	(0, 200)	1.0	4.27	43.0	12.6	0.54
20	(0, 200)	1.2	4.97	41.6	41.6	2.10
60	(0, 200)	1.2	4.56	41.8	41.6	1.90
20	(133, 100)	1.0	4.30	70.8	12.6	0.54
60	(133, 100)	1.0	4.30	70.8	12.6	0.54
20	(133, 100)	1.2	5.40	69.3	41.6	2.20
60	(133, 100)	1.2	4.80	69.5	41.6	2.00
20	(267, 0)	1.0	4.33	98.6	12.6	0.55
60	(267, 0)	1.0	4.33	98.6	12.6	0.55
20	(0, 300)	1.0	4.27	127.6	12.6	0.54
60	(0, 300)	1.0	4.27	127.6	12.6	0.54

in the lower root zone could indicate sufficiently low potentials and conductivities to virtually eliminate drainage. Automated sprinkler or drip systems with switching tensiometers located in the upper root zone could probably be used to automatically limit irrigation amounts.

For the conditions modeled, the model indicated a relatively rapid mineralization of available organic-N of about 6.5% per day. The word "available" is used to suggest that some organic-N would not be mineralized. Therefore, if green crop residue is incorporated into a warm, wet soil in late summer, it is possible that much of the nitrogen would be mineralized and available for leaching by winter rains.

Fertilization can increase nitrate-N concentrations in leachate to levels in excess of 10 ppm. This can occur even with moderate fertilizer applications (133 to 200 kg/ha) and reasonably good irrigation management. Organic matter decomposition can cause leachate concentrations ≧10 ppm nitrate-N. However, it is probable that high leachate concentrations of nitrate-N can be avoided even with fertilization for good yields. To achieve this desirable result, a decision-making process as suggested in Figure 113 may need to be adopted.

Bromide Movement as Affected by Excess Water

As previously discussed, bromide was determined to be an excellent indicator of nitrate movement. During 1973 and 1974, bromide was added using different methods of application to selected plots in the various irrigation systems (Sprinkler Plots 6, 7, 8, 9, 12, and 13; Furrow Plots 18, 19, 20, 23, 24, and 25; Subirrigation Plots 32, 33, 34, 35, 38, 39, 40, and 41). Different amounts of irrigation water were added and records of the rainfall were obtained. Although some of the plots were irrigated with an amount equal to potential ET as previously discussed, measurements of soil-water content were made to obtain better estimates of the actual ET of the crop. Rainfall received between the 1973 and 1974 growing seasons was adjusted by eliminating showers less than 6 mm and subtracting 6 mm from rains greater than 6 mm. Bromide was determined on soil samples as previously described periodically during the two-year period.

The data obtained are shown in Figure 114. The high r value of .879 indicates a good relationship between the two parameters. The scatter of the data (Figure 114) is not surprising in view of the variability in texture below the surface (Figure 10, p. 40) and the different types of water movement from the different irrigation systems. The piston movement of the bands described in the previous section was exhibited to a large extent all the way to the water table located at 5.5 m. The scatter of the points at 5.5 m would suggest that less water is needed to move the bromide to this depth than indicated by the regression line. However, since this is the depth of the water table, less actual water may have been required to move the bromide to this depth, and little movement occurred once the bromide reached this depth as diffusion is a relatively slow process.

The scatter of the points between 1.8 and 4.3 m could probably be explained by including a correction factor for soil texture from each of

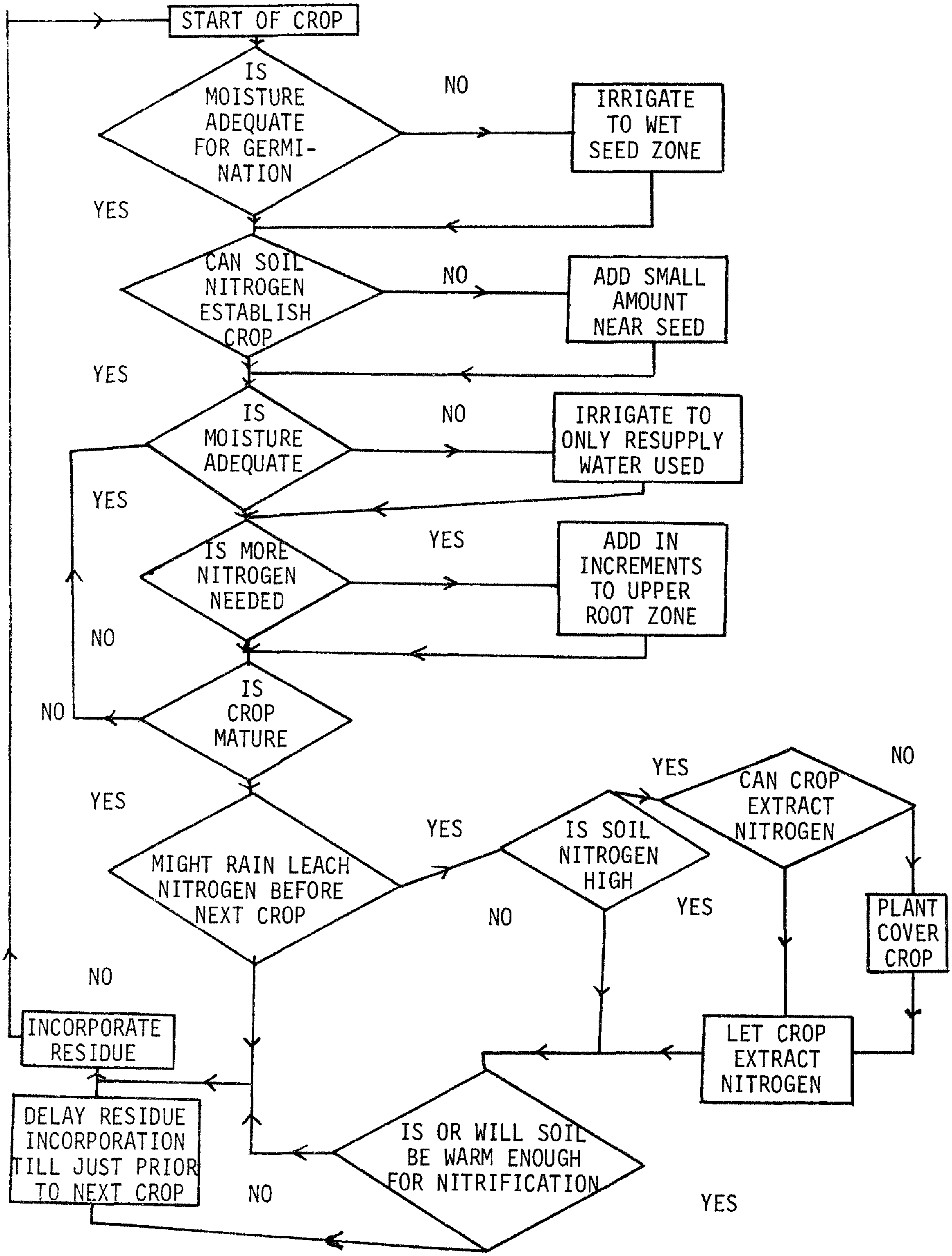


Figure 113. Decision flow chart for limiting leaching of nitrate-N from sandy soils.

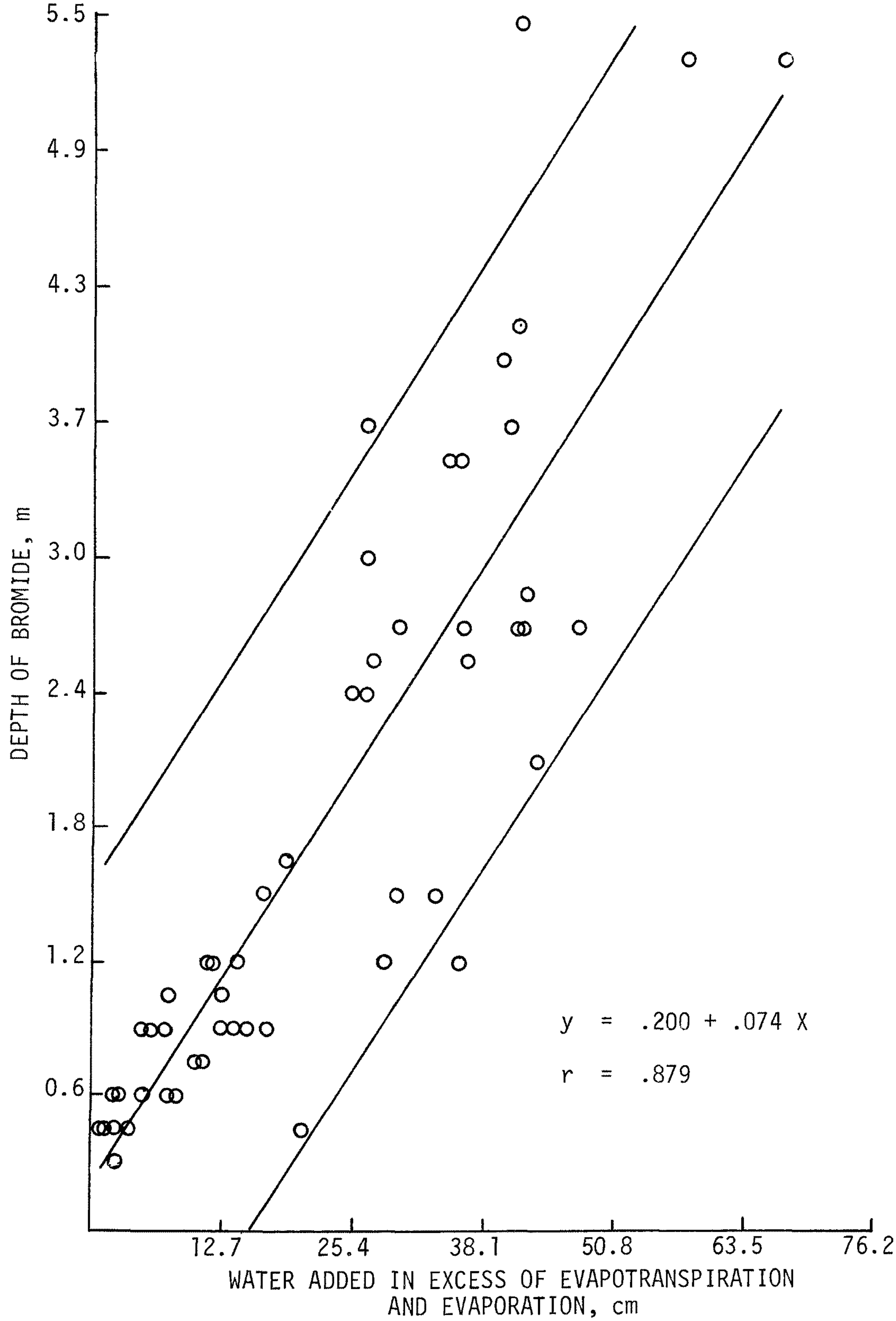


Figure 114. Relationship between depth of bromide and water added in excess of evapotranspiration and evaporation.

the different plots. However, from a practical standpoint, this does not seem necessary. These samples were obtained from a 4-ha block of land typical of the area. From the standpoint of irrigation return flow, the interest will be relative to a given large area rather than from a specific plot with a specific texture because detailed sampling such as occurred at this location will not be possible over the area of this soil series due to expense. The regression equation on Figure 114 indicates that for each cm of water in excess of evaporation and ET the bromide moved 7.4 cm. Between sweet corn crops, 15.2 to 25.4 cm of rainfall in excess of evaporation were received during the studies between 1971 and 1974. Thus, excess nitrate in the profile at the end of the season could be expected to reach the water table in three to five years if a crop such as sweet corn were grown from rainfall received between growing seasons. The furrow irrigation systems commonly used in the area are very inefficient. The experience with furrow irrigation in this study indicates that two to three times the amount of water necessary for crop production may be applied or 30.5 to 60.9 cm excess water. If this is the case, it is possible that excess nitrate may be moved to the water table in one to two years due to a combination of rainfall and excess irrigation water.

In summary, the regression equation obtained from bromide data indicates that for each cm of water added in excess of ET and evaporation, nitrate (which moves similar to bromide) will move down 7.4 cm in the profile. If a crop such as sweet corn is grown, excess nitrate in the profile can be expected to reach the water table in three to five years from rainfall between crops. If excess water is applied during the growing season, it may reach the water table in one to two years.

OBJECTIVE 2 - POTENTIAL OF USING MODIFIED CURRENT IRRIGATION AND FERTILIZATION PRACTICES FOR IMMEDIATE REDUCTION OF POTENTIAL POLLUTION

Several modifications to current irrigation and fertilization practices were investigated as to their potential to enhance the quality of irrigation return flow. A discussion of these modifications follows.

Furrow Irrigation Systems

Fertilizer Placement--

One simple modification was to apply the fertilizer in the bed rather than below the level of the water furrow. Figure 115 shows the results obtained during 1973 in a furrow-irrigated plot to which ammonia was applied. It can readily be seen that the nitrate-N content of the soil-water extracts was much higher in the surface 1.2 m than where the fertilizer was banded below the level of the water furrow (Figure 96) or in the control plot (Figure 92). Values of 64 and 594 ppm nitrate-N were obtained at depths of 0.3 and 0.6 m, respectively, compared to values of 20 and 15 ppm or less where the fertilizer was banded below the level of the water furrow and where no fertilizer, respectively, were the treatments. There was an increase in the nitrate-N concentration of the soil-water extracts between 1971 and 1973 at 4.6 and 6.1 m (Figure 116). However, the final concentrations at these depths were only 4 to 8 ppm greater than plots where no fertilizer was applied (Figure 95) or the fertilizer was applied below

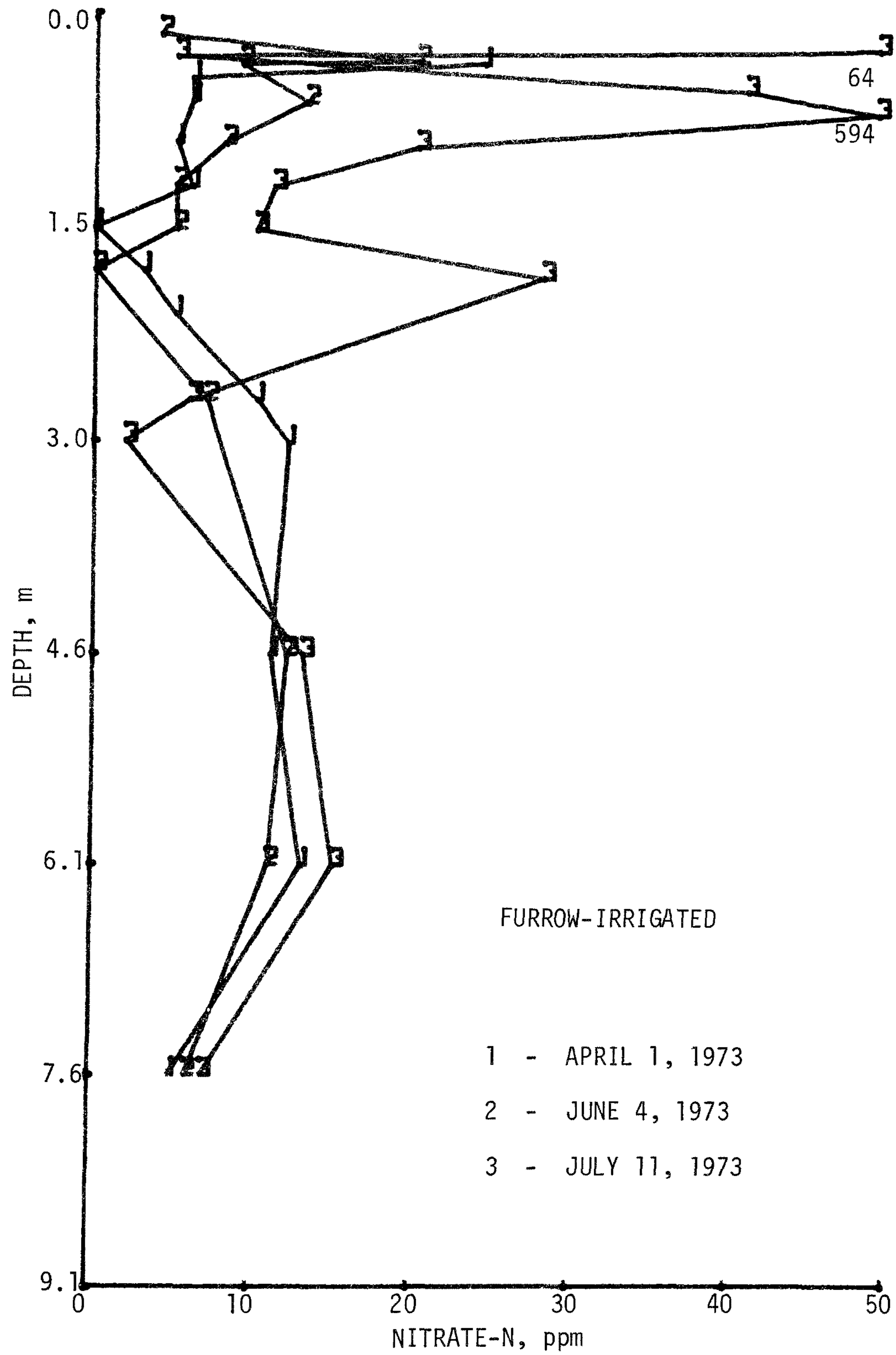


Figure 115. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a plot treated with anhydrous ammonia banded in the bed.

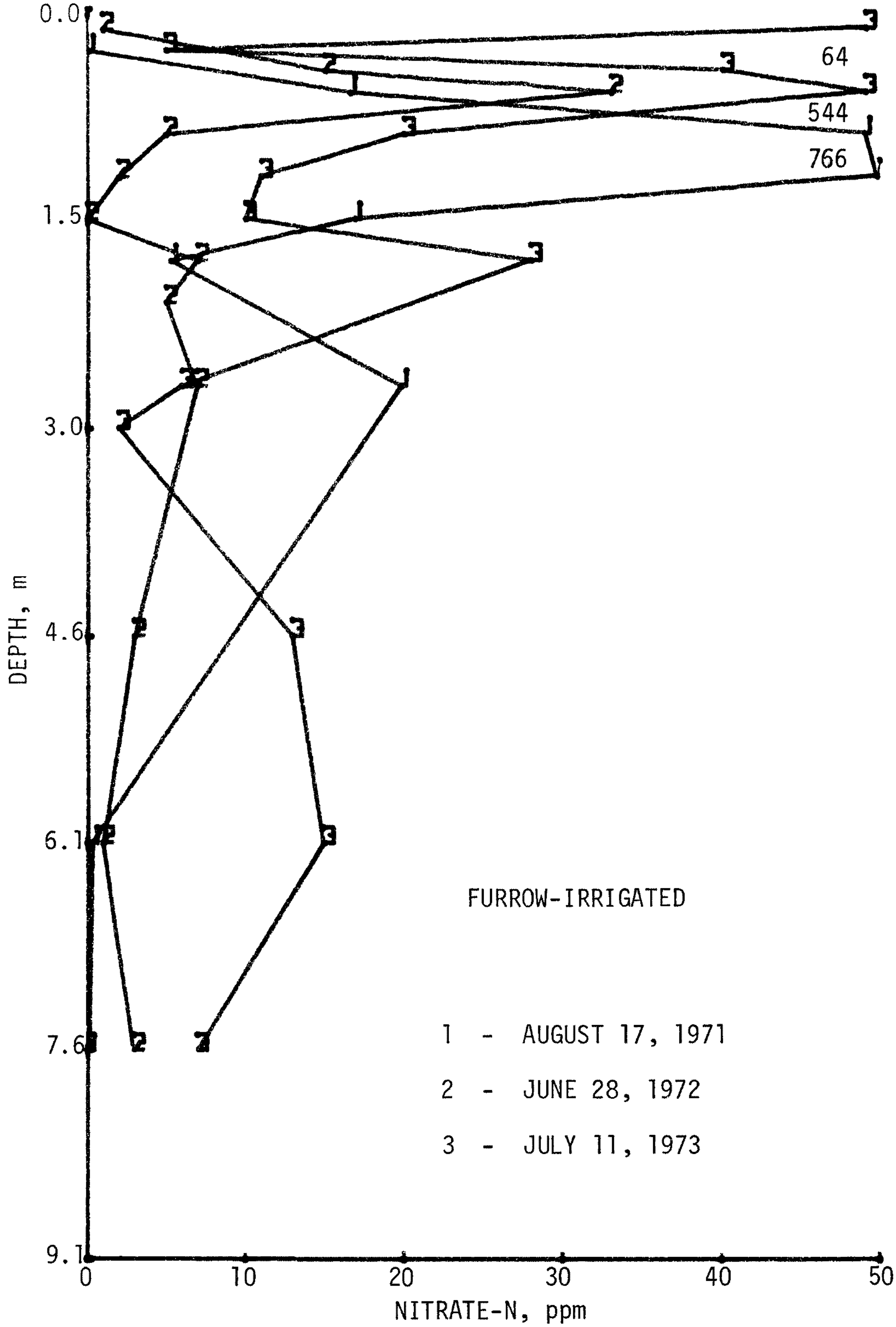


Figure 116. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with anhydrous ammonia banded in the bed.

the water furrow (Figure 97). These differences could be considered minor and would probably not offset the value of the increased nitrate-N in the root zone.

Differences between methods of applying anhydrous ammonia can more easily be seen in a direct comparison of the nitrate-N concentrations in 1973 of the porous bulb soil-water extracts when anhydrous ammonia was applied in the bed both above and below the bottom of the water furrow (Figure 117) in the furrow-irrigated system. The previously discussed nitrate-N concentrations were higher at all depths where anhydrous ammonia was applied above rather than below the water furrow. The desirable large higher concentrations in the root zone (<1.0 m) will probably offset the smaller higher concentrations below the root zone (>1.5 m).

The analyses of soil extracts (Figure 118) from samples obtained in 1974 also give credence to the idea that anhydrous ammonia banded in the bed may be superior to anhydrous ammonia banded below the level of the water furrow. These data show that the nitrate-N was higher in the root zone (0 to 1.5 m) where the ammonia was applied in the bed and higher below the root zone (2 to 3.8 m) where anhydrous ammonia was banded below the level of the water furrow.

Neither the concentration of nitrate-N of the porous bulb extracts obtained in 1973 nor the extracts from soil samples obtained in 1974 from both methods of placement at depths below the root zone were high enough to be of concern. However, there was a trend for the placement in the bed to be superior over placement below the water furrow.

Uran was also banded in the bed in the furrow-irrigated plots. The nitrate-N content of the soil-water extracts in 1973 was not as high where the Uran was banded (Figure 119) as where ammonia was banded (Figure 115) in the bed. This might be due to the fact that some of the Uran nitrogen was already in the nitrate form and more readily absorbed by the crop while it was necessary for the ammonia to be converted to nitrate. The highest values for the ammonia plots were obtained at the end of the growing season when there were no plants to utilize the nitrogen.

With the exception of a high value for nitrate-N at 0.5 m in the plot where the Uran was banded below the water furrow (Figure 99) and at 0.9 m where the nitrogen was banded in the bed (Figure 119), there was little difference in the two treatments in the root zone. Below 1.5 m, however, the nitrate-N concentration of the soil-water extracts was significantly higher where the Uran was banded below the water furrow (Figure 99) than where it was banded in the bed (Figure 119). The same was true between 1971 and 1973. The nitrate-N concentration in the root zones (0 to 1.5 m) was higher where the fertilizer was banded in the bed (Figure 120). Between 1.5 and 7.6 m, however, the nitrate-N of the soil-water extracts was much higher at the end of the three-year period where the Uran was banded below the water furrow (Figure 100) than above the water furrow.

A direct comparison between plots where Uran was banded in the bed and below the level of the water furrow (Figure 121) in 1973 also emphasizes the

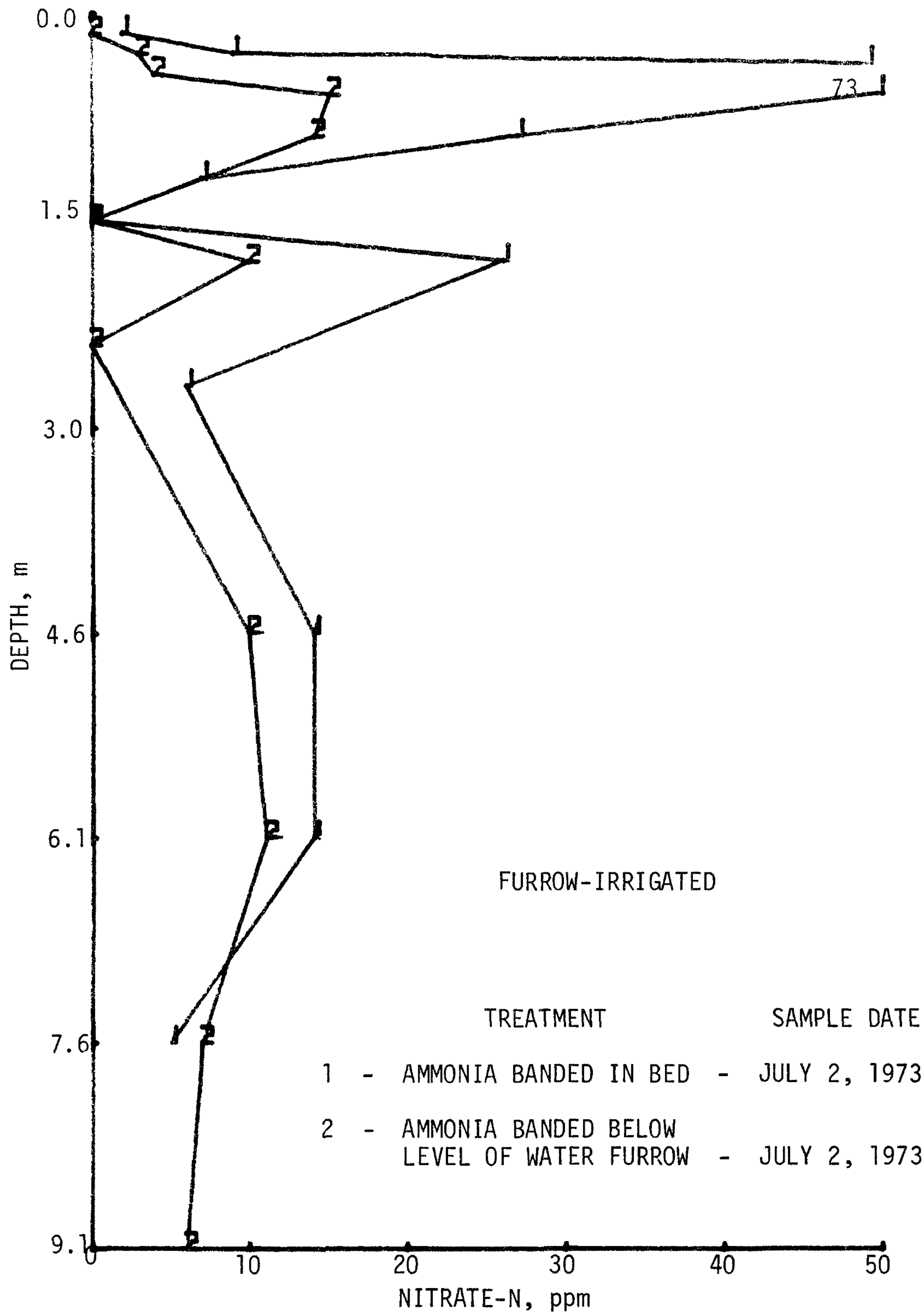


Figure 117. Porous bulb soil-water extract nitrate-N concentrations by soil depth for plots treated with anhydrous ammonia banded at different depths for three years, 1973. (Total N - 374 kg/ha)

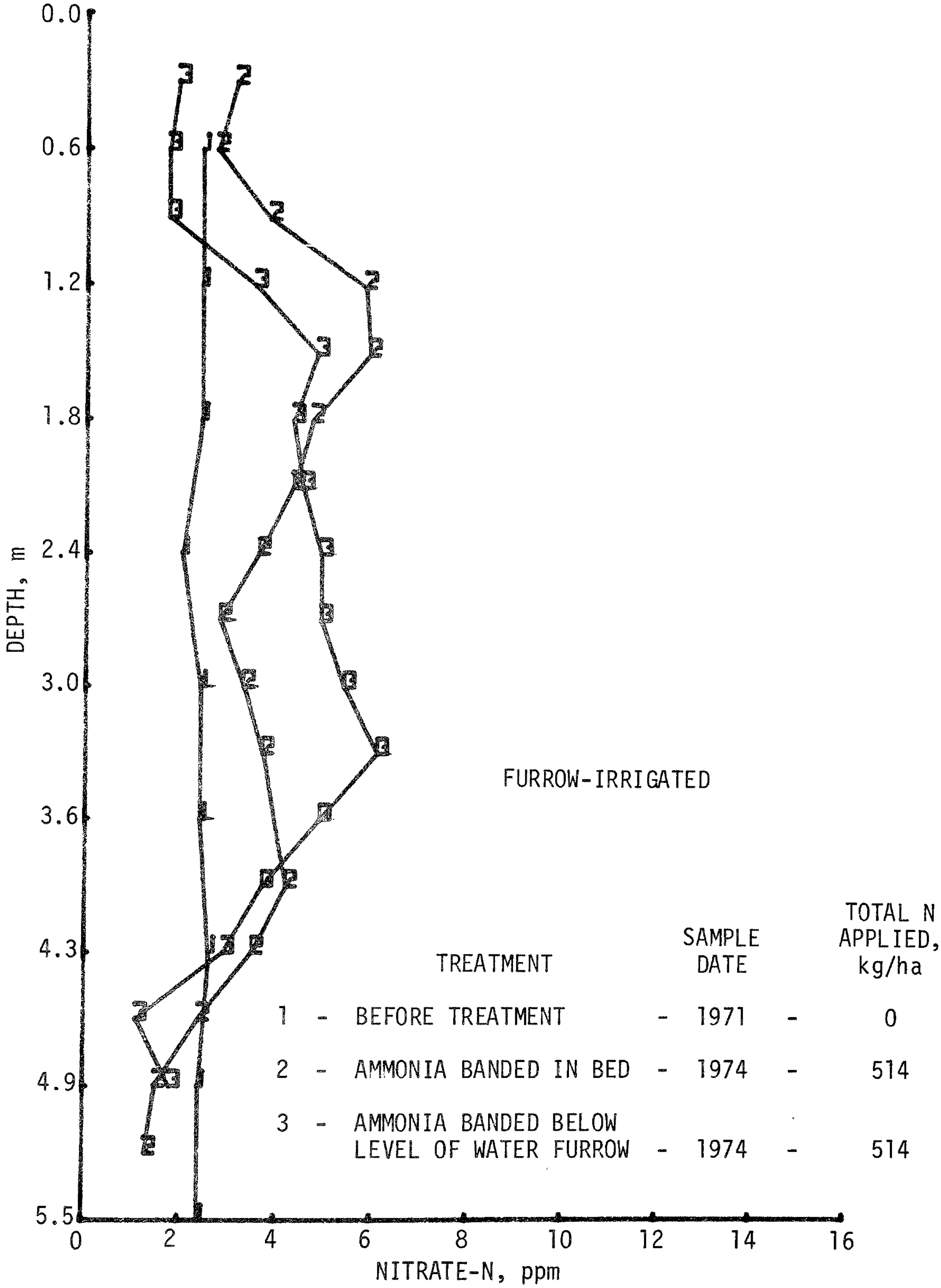


Figure 118. Soil extract (1:1) nitrate-N concentrations by soil depth before treatment (1971) and after four years of N application, 1974.

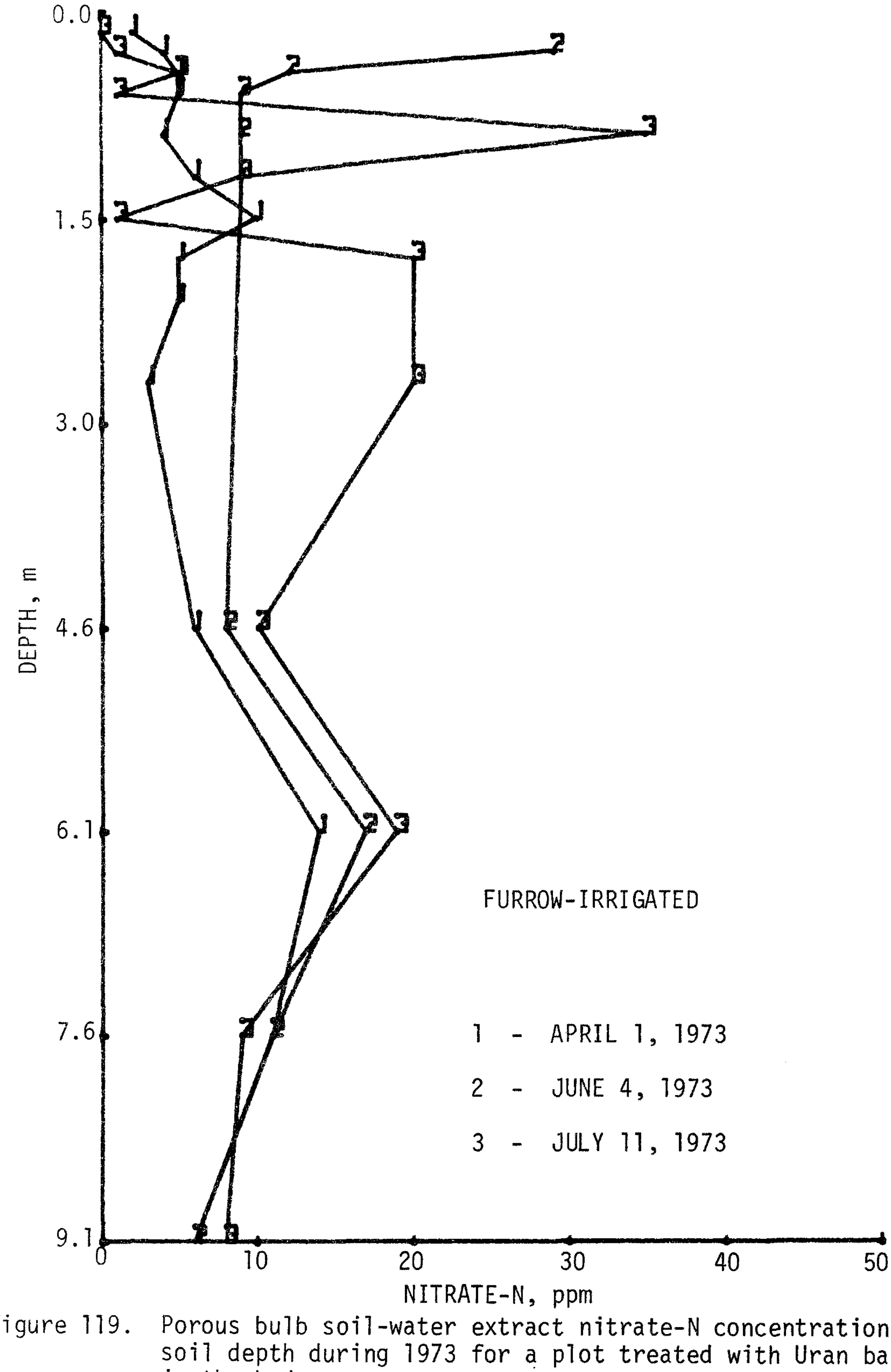


Figure 119. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a plot treated with Uran banded in the bed.

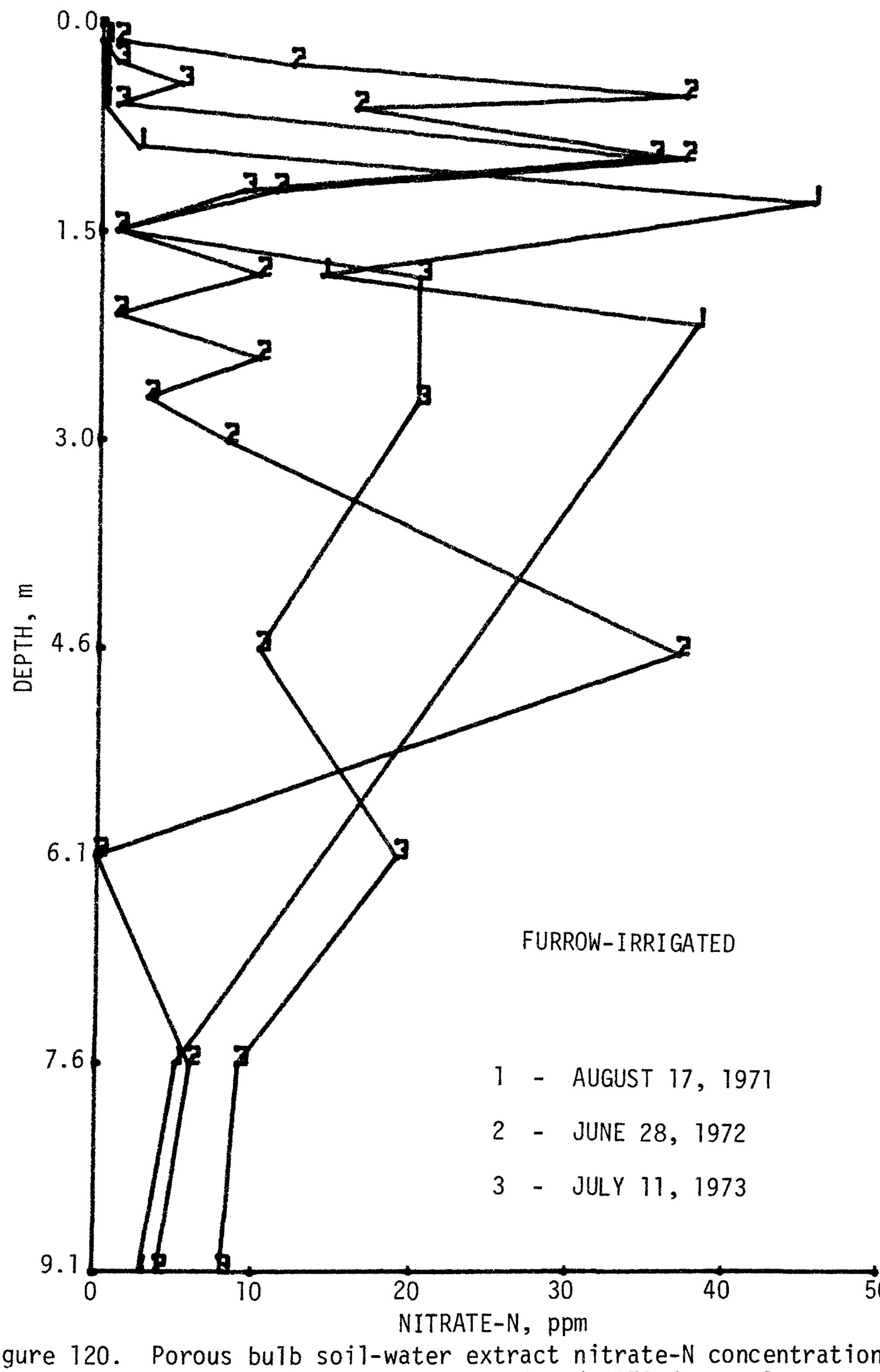


Figure 120. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with Uran banded in the bed.

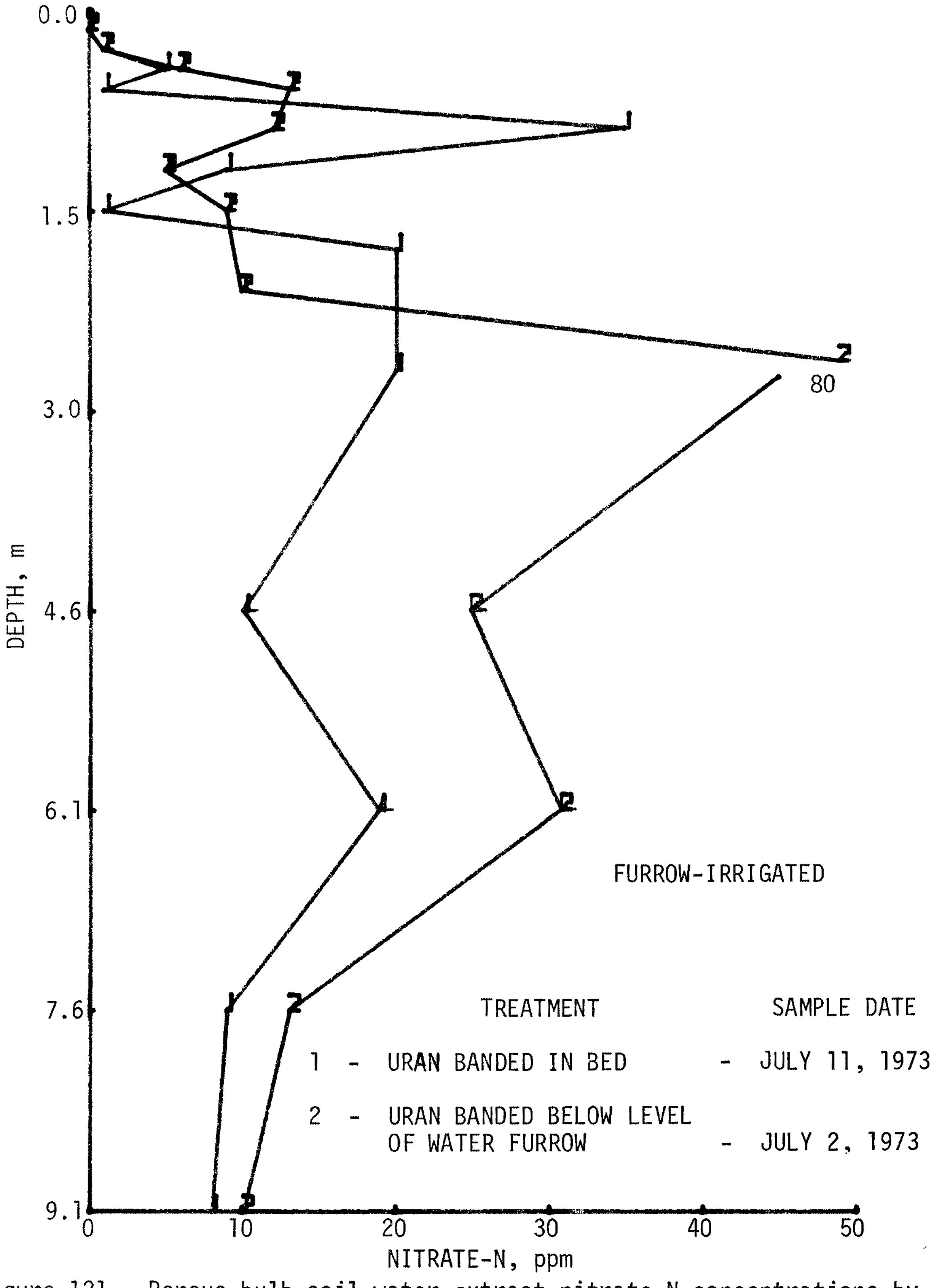


Figure 121. Porous bulb soil-water extract nitrate-N concentrations by soil depth for plots treated with Uran banded at different depths for three years, 1973. (Total N - 368 kg/ha)

higher concentration of nitrate-N in this zone. The nitrate-N concentration of porous bulb samples where Uran was banded below the level of the water furrow was significantly higher compared to Uran banded in the bed or any of the ammonia treatments (Figure 117).

When extracts from soil samples are compared from plots where Uran was applied above and below the water furrow (Figure 122), it can be seen that there was a major increase in nitrate-N in the surface 1.8 m between 1971 and 1974. The increase was greater where the Uran was applied below the level of the water furrow than above the level of the water furrow. This nitrogen would still be available for plant growth if leaching did not occur and is much higher than samples obtained from anhydrous ammonia-treated plots (Figure 118). Below 1.8 m, samples from the anhydrous ammonia-treated plots contained more nitrate-N than samples from the Uran-treated plots (Figure 122).

Sulfur-Coated Urea--

Sulfur-coated urea was banded in the bed for all irrigation systems. In the furrow irrigation system, the values for nitrate-N in the soil-water extracts were generally low both within the root zone (0 to 1.5 m) and below the root zone (>1.5 m) during 1973 (Figure 123) and 1971-1973 (Figure 124). The exception to this was the data obtained on July 11, 1973 between 1.5 and 3.0 m. These data indicate that some nitrate was made available from the sulfur-coated urea that was not utilized by the crop. With the exception of this date, the nitrate-N of the soil-water extracts was similar to that obtained from the unfertilized plots both during 1973 (Figure 123 vs Figure 92) and 1971-1973 (Figure 124 vs Figure 95). The values were much less than any of the previously discussed treatments.

Ammonia + N-Serve--

During 1971, both ammonia (Figure 125) and ammonia + N-Serve (Figure 126) were treatments in the study. In both treatments the nitrate-N was high in the root zone (0 to 1.5 m). Below 1.5 m there was little difference between the two treatments. Since the N-Serve did not delay the conversion of ammonia to nitrate and there was no increase in yield through using N-Serve, treatments with N-Serve were discontinued at the end of the 1971 growing season.

Sprinkler Irrigation System

Fertilizer Placement--

Treatments, with the exception of different vertical placements, discussed above for the furrow irrigation systems were also evaluated on the sprinkler irrigation system. Where ammonia was applied in the bed in 1973 (Figure 127), nitrate-N concentration of the soil-water extracts was high in the root zone. The concentrations were higher than in the unfertilized plot (Figure 90) and similar to the values obtained where ammonia was applied in the bed in the furrow-irrigated plot (Figure 115). Nitrate-N was high in the root zone (0 to 1.5 m) at the end of the growing season 1971 through 1973 (Figure 128). Below 2.1 m there was a concentration increase in the soil-water extracts between 1971 and 1973. The increases relative to depth and amount were greater than the values obtained in the

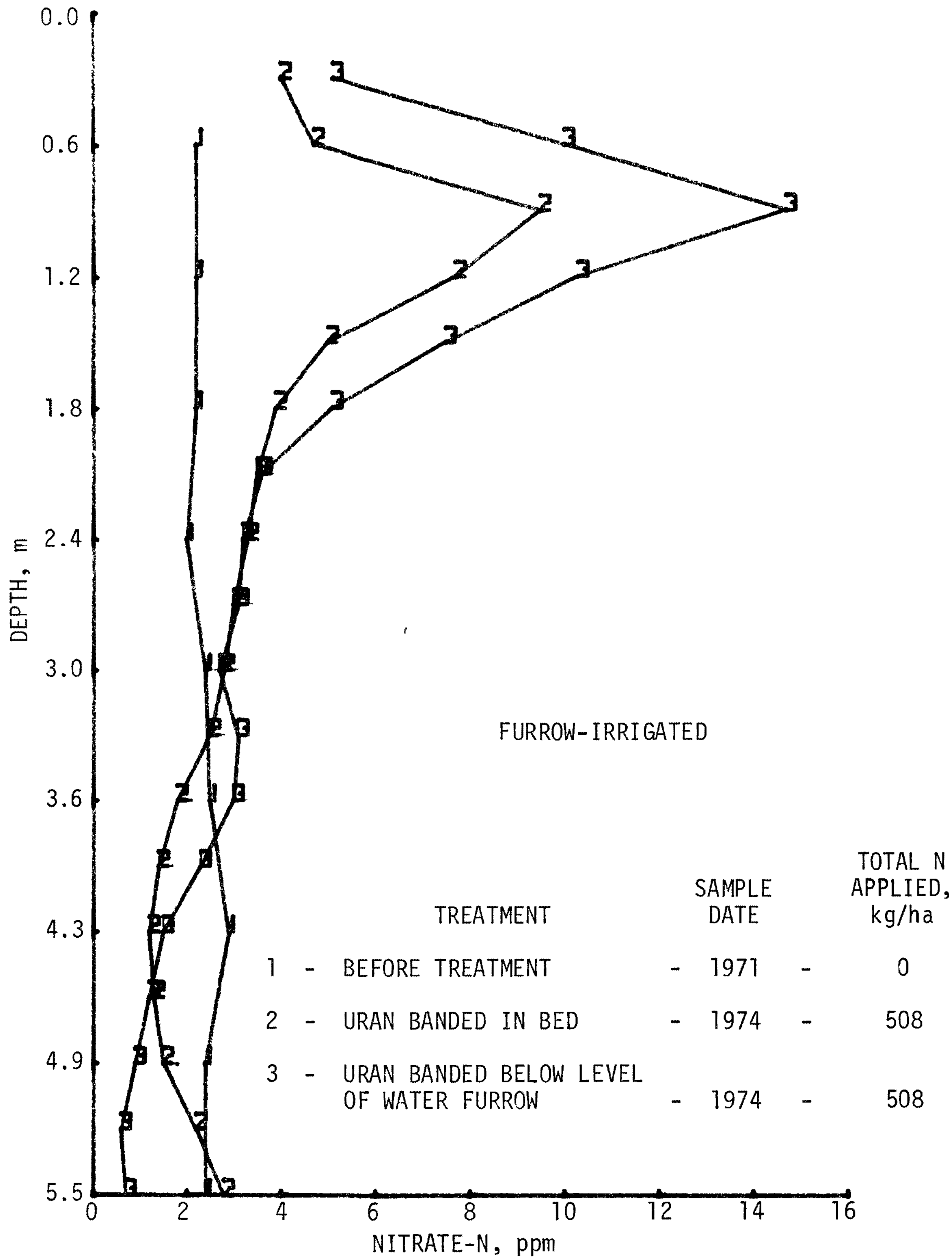


Figure 122. Soil extract (1:1) nitrate-N concentrations by soil depth before treatment (1971) and after four years of N application, 1974.

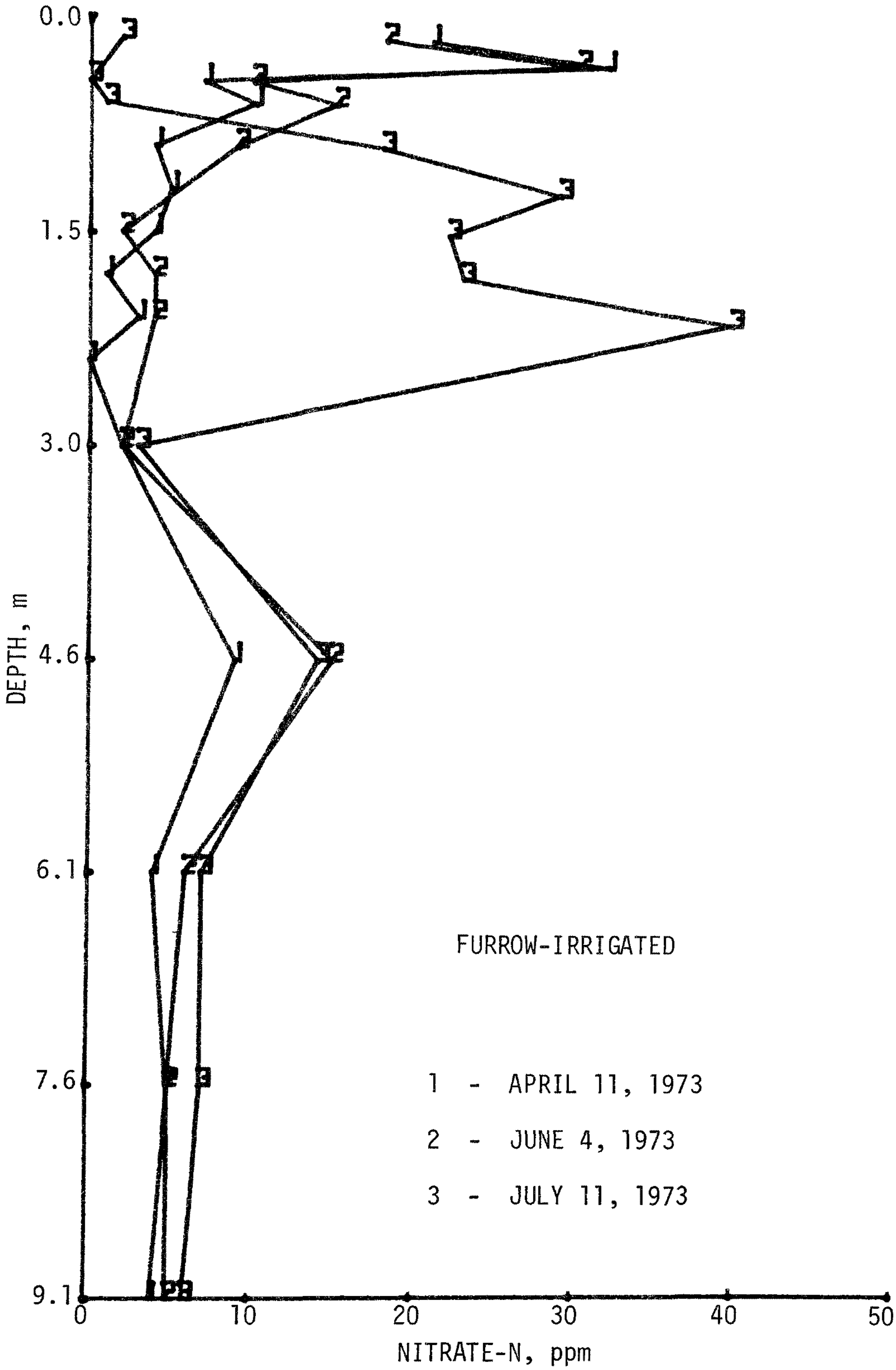


Figure 123. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a plot treated with sulfur-coated urea banded in the bed.

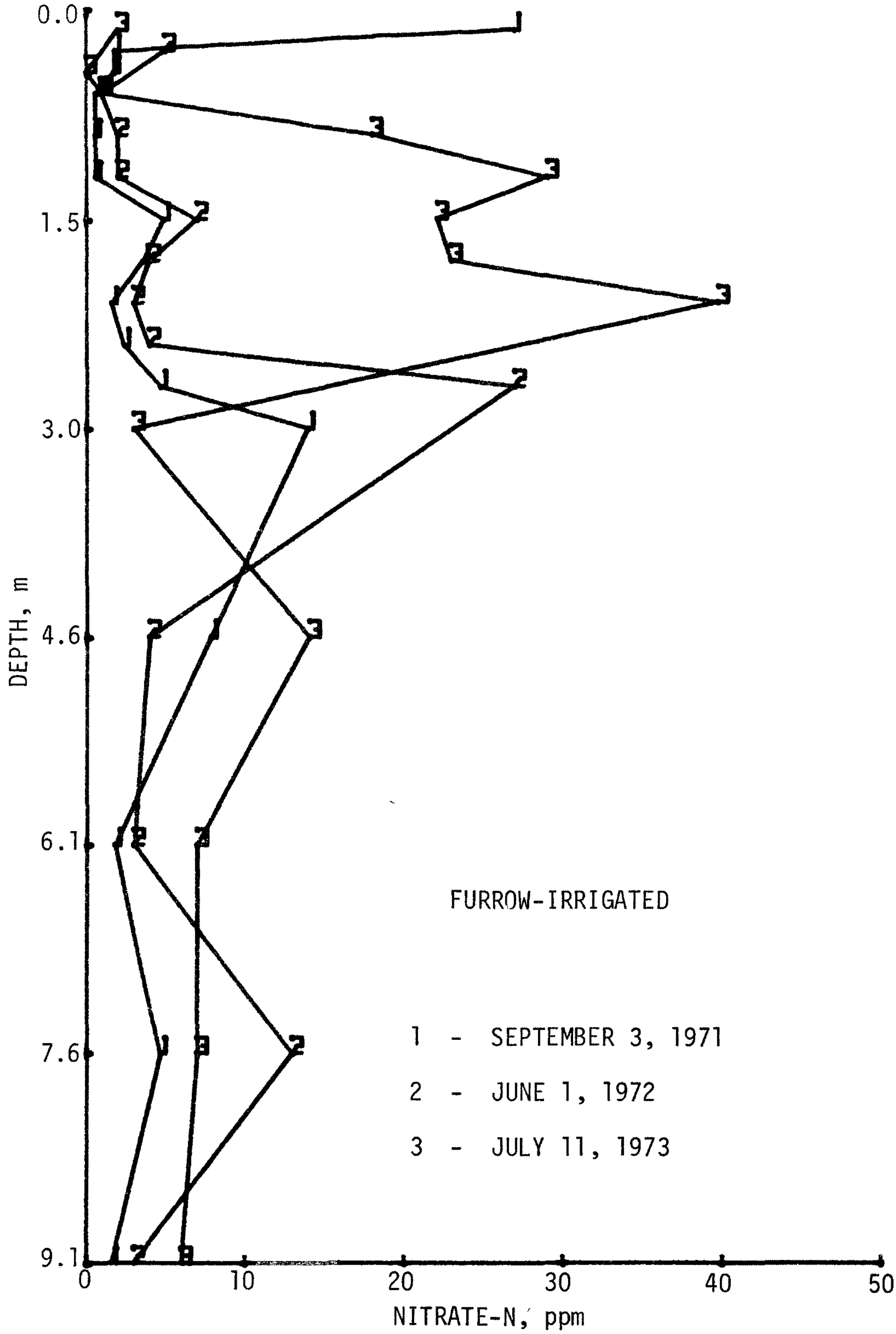


Figure 124. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with sulfur-coated urea banded in the bed.

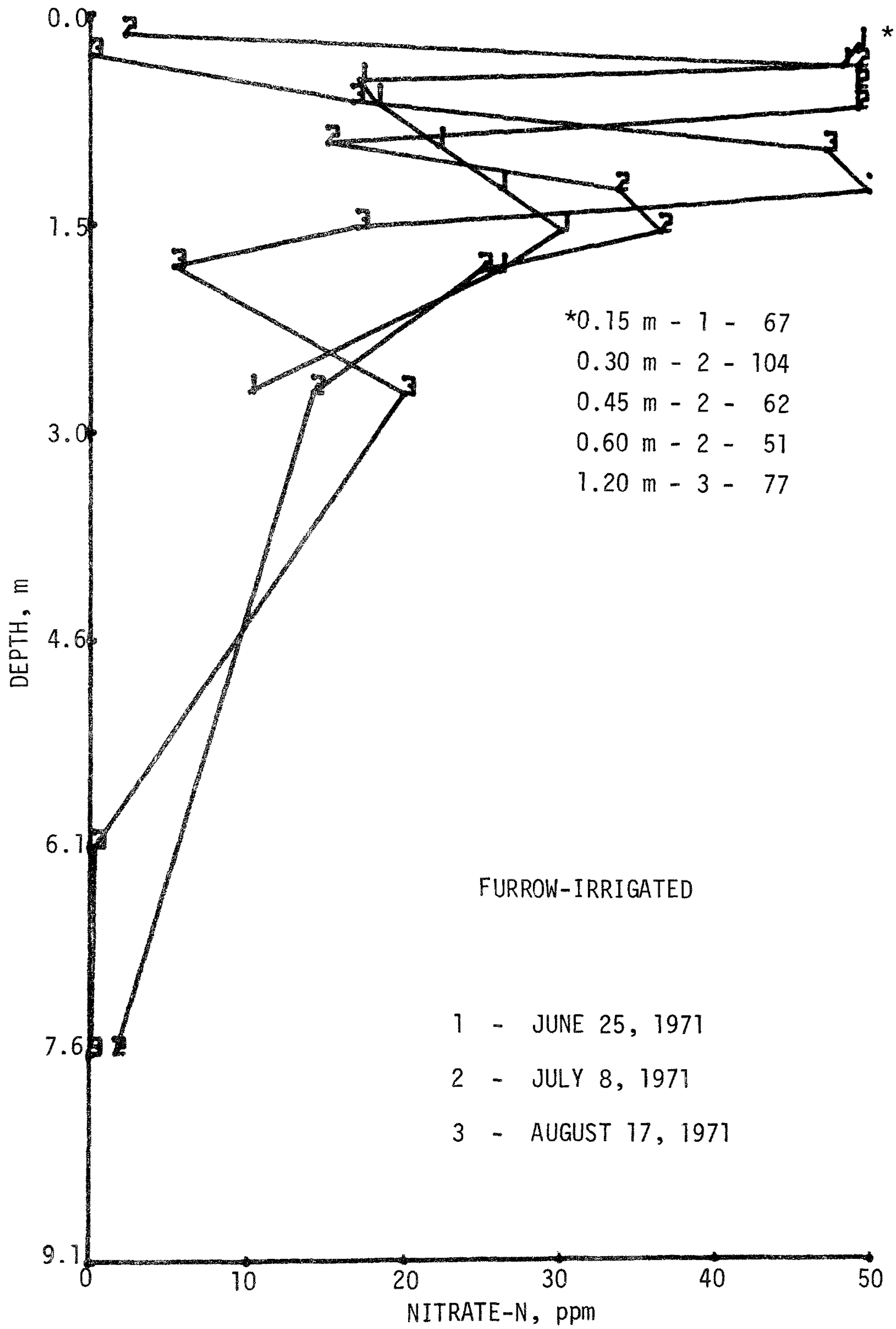


Figure 125. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971 for a plot treated with anhydrous ammonia banded in the bed.

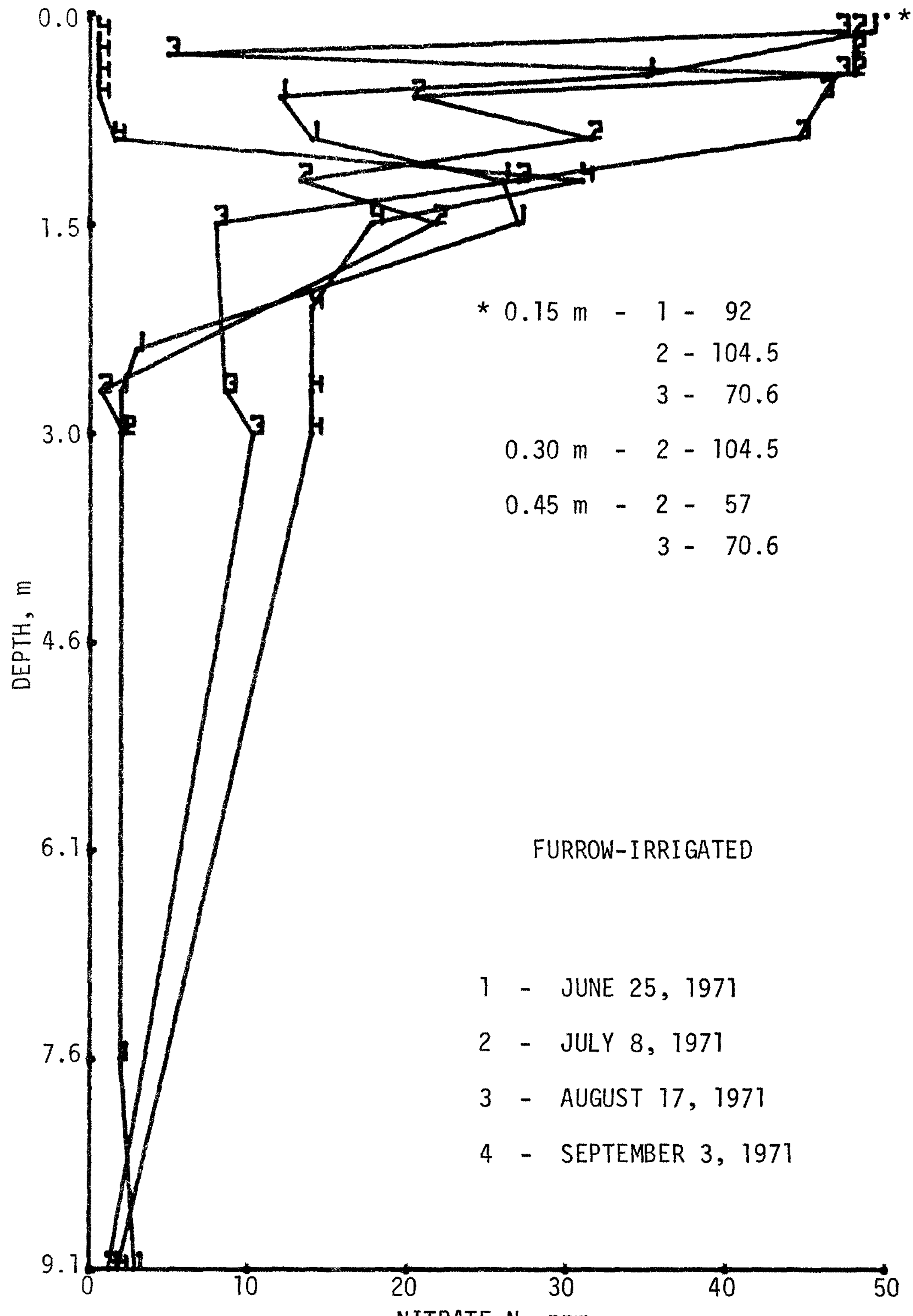


Figure 126. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971 for a plot treated with anhydrous ammonia + N-Serve banded in the bed.

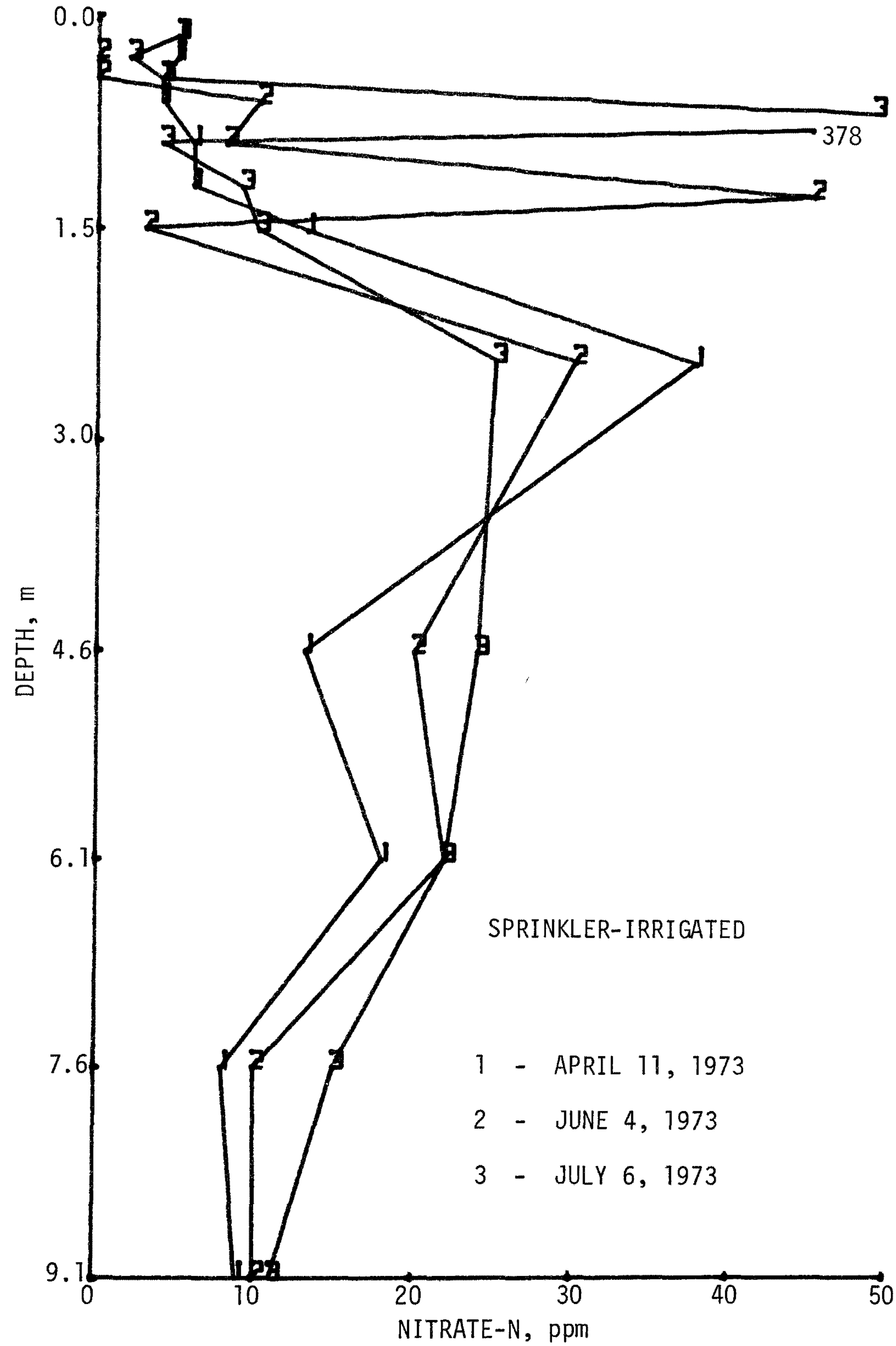


Figure 127. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a plot treated with anhydrous ammonia banded in the bed.

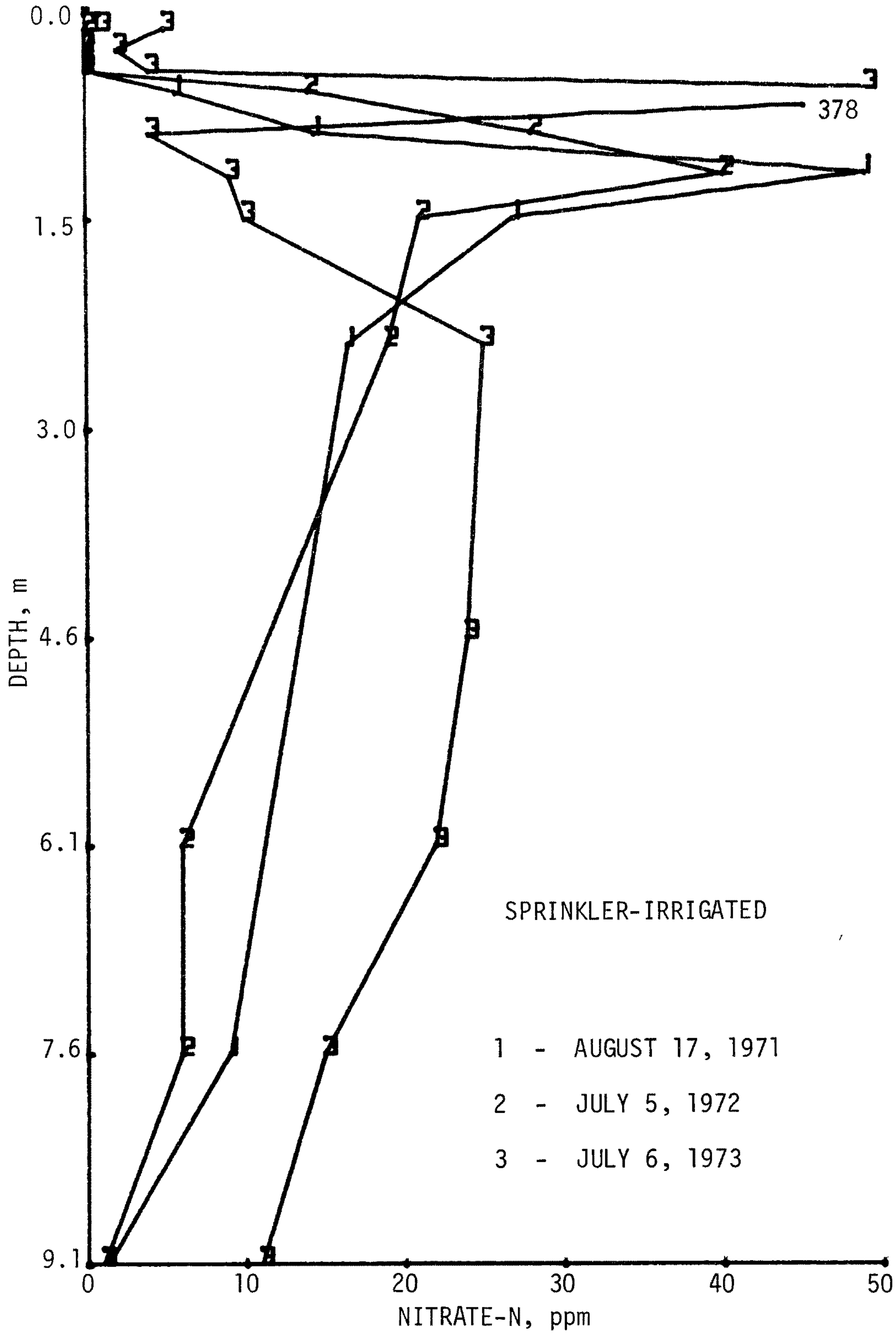


Figure 128. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with anhydrous ammonia banded in the bed.

unfertilized plot (Figure 93). The increases can more easily be seen when a control plot is compared directly with a plot where anhydrous ammonia was applied in the bed over the three-year period (Figure 129). The nitrate-N concentration of the porous bulb extracts was significantly higher where anhydrous ammonia was applied over the three-year period.

Nitrate-N concentration of soil-water extracts where Uran was applied in the bed (Figure 130) were, in general, lower than in the unfertilized plot (Figure 90). The concentrations were thus much less than those in the plot fertilized with ammonia on the same date (Figure 127). With the exception of the concentration of 52 ppm at 1.2 m, the nitrate-N concentrations where Uran was banded in the bed (Figure 131) were less than in the unfertilized plot (Figure 93) between 1971 and 1973.

Soil data obtained in 1974 where Uran was banded in the bed in the sprinkler irrigation system (Figure 108) also showed little change between 1971 and 1974. The nitrate-N concentration in soil extracts of samples from the sprinkler-irrigated plot was much less than where Uran was applied either in the bed or below the level of the water furrow in the furrow irrigation system (Figure 122). Also included in Figure 108 are nitrate-N data from a plot where anhydrous ammonia was applied for four years in the bed in a sprinkler-irrigated plot. The nitrate-N concentrations where anhydrous ammonia was applied were higher than those obtained where Uran was applied in the sprinkler irrigation system and were approximately equal to those obtained where anhydrous ammonia was banded in the bed in the furrow irrigation system (Figure 118). The data thus indicate that fertilizer applied in the bed is one of the better treatments to minimize nitrate-N concentrations in the soil solution below the root zone under sprinkler irrigation.

Sulfur-Coated Urea--

The soil-water extracts from plots fertilized with sulfur-coated urea under sprinkler irrigation (Figure 132) in 1973 were much higher in nitrate-N than the extracts from the sulfur-coated, urea-fertilized, furrow-irrigated plot (Figure 123) and the unfertilized plot (Figure 90) at 3.0 to 6.1 m and lower at 0.6 to 3.0 m. Changes between 1971 and 1973 in the sulfur-coated urea sprinkler-irrigated plot (Figure 133) compared to the furrow-irrigated plot (Figure 123) and the unfertilized plot (Figure 93) followed the same trend. Nitrate-N in extracts from soil samples obtained in 1974 showed an increase in furrow-irrigated plots from 3.0 to 5.5 m (Figure 134) and an increase in sprinkler-irrigated plots from 0.6 to 3.0 m (Figure 134), thus indicating the same trend.

Irrigation Criteria

Criteria for applying irrigation water were (a) visual (when significant leaf curl occurred), (b) when tensiometers reached -20 cb potential at 30 cm and (c) when tensiometers reached -40 cb potential at 30 cm. In 1971, approximately 7.62 cm of water were applied, and in 1972-3, water equal to the potential ET in a given time period was applied when the above-mentioned criteria were met. As previously discussed, problems were encountered in production of the corn crop in 1971 and 1972. In 1971, the seed quality was poor, and in 1972, poor initial plant development occurred due to a nitrogen

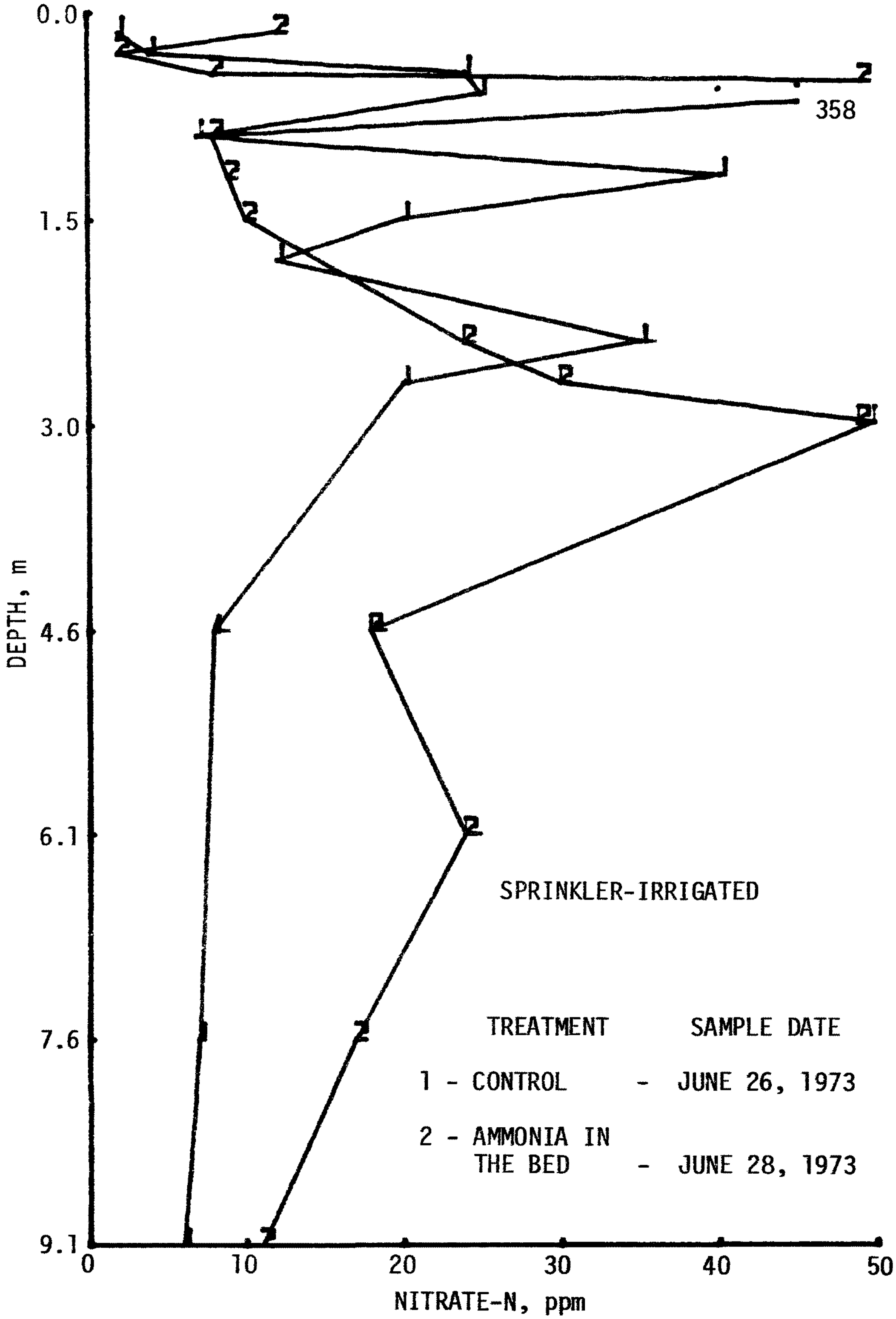


Figure 129. Porous bulb soil-water extract nitrate-N concentrations by soil depth for a control plot and a plot treated with anhydrous ammonia for three years, 1973. (Total N - 374 kg/ha)

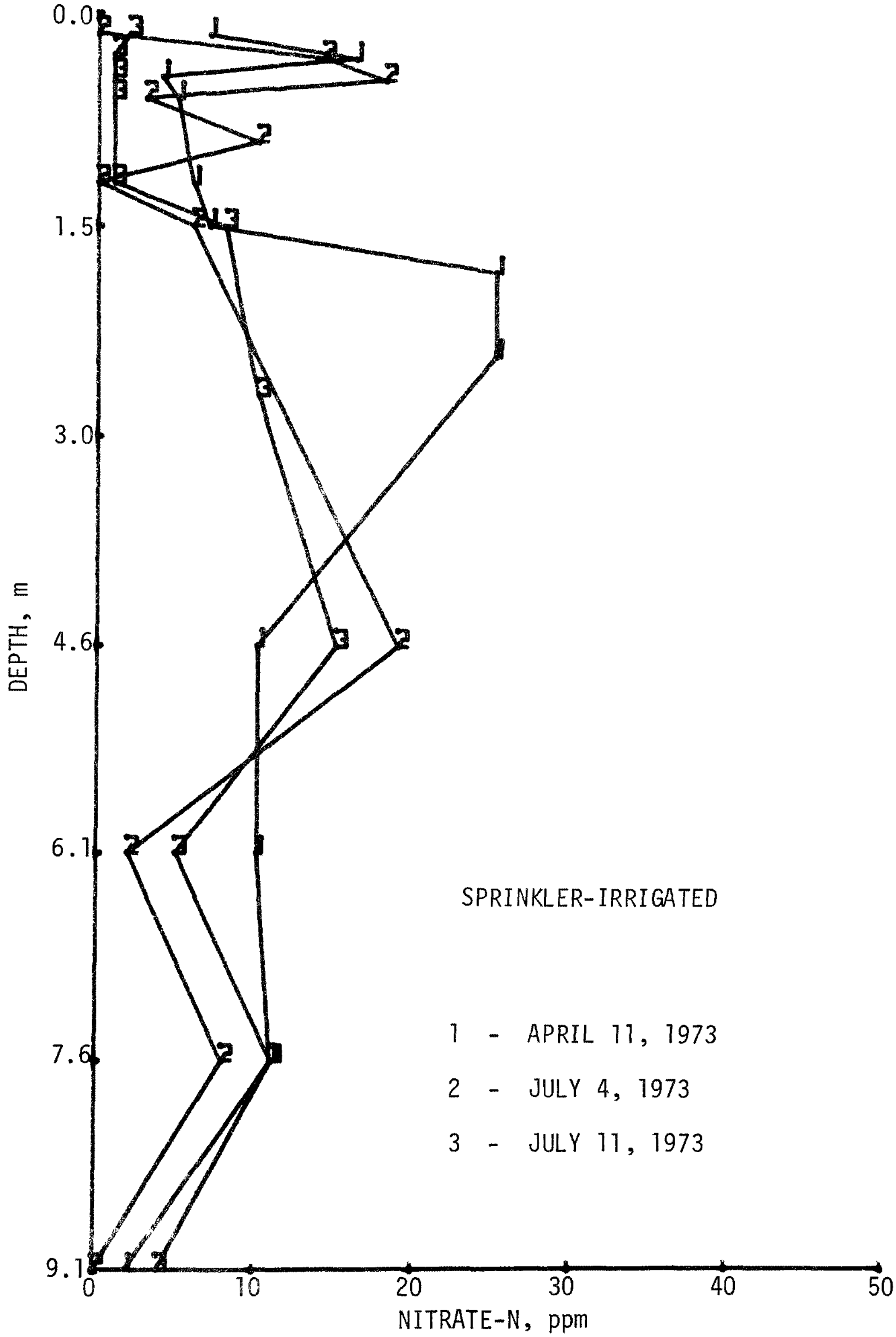


Figure 130. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a plot treated with Uran banded in the bed.

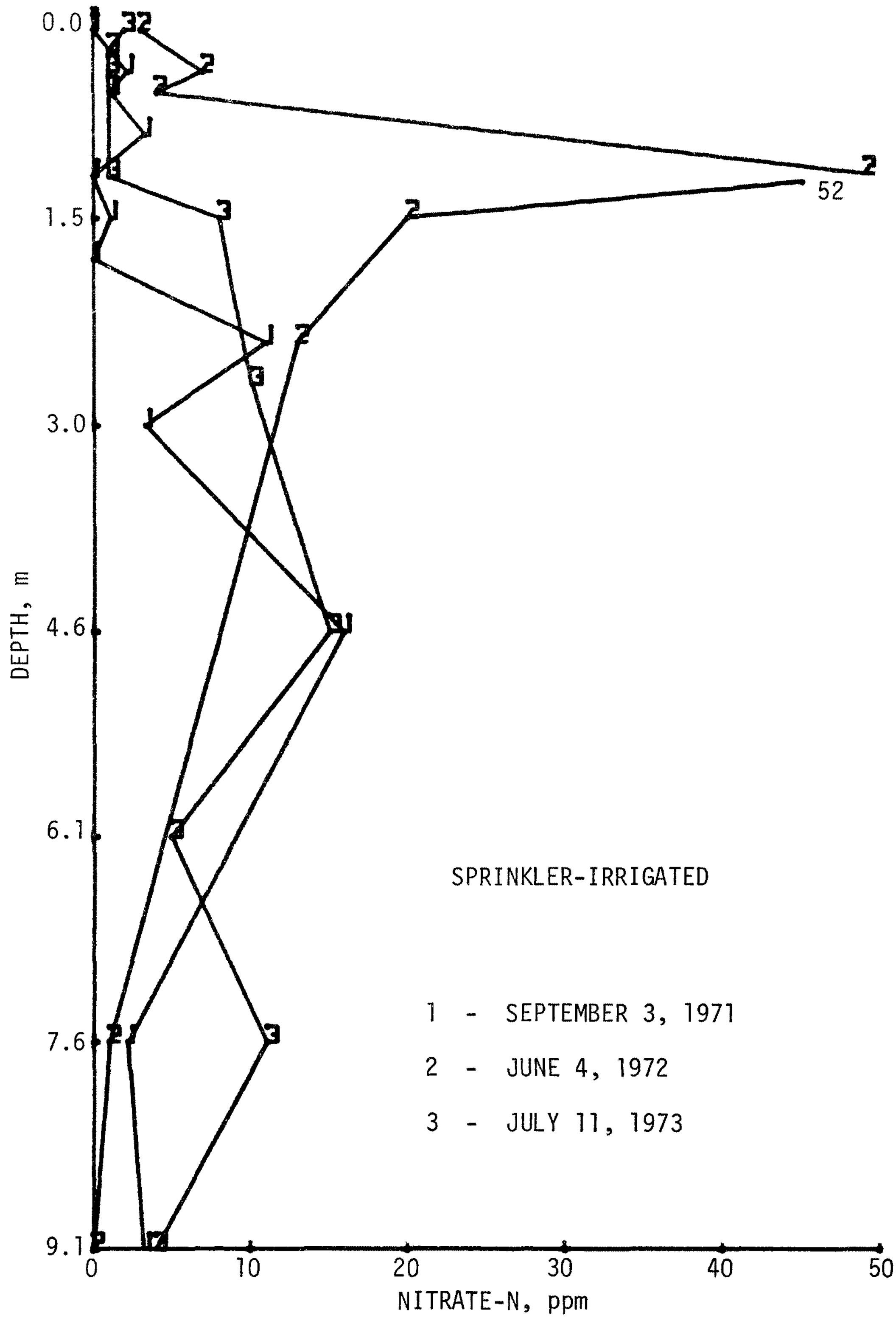


Figure 131. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with Uran banded in the bed.

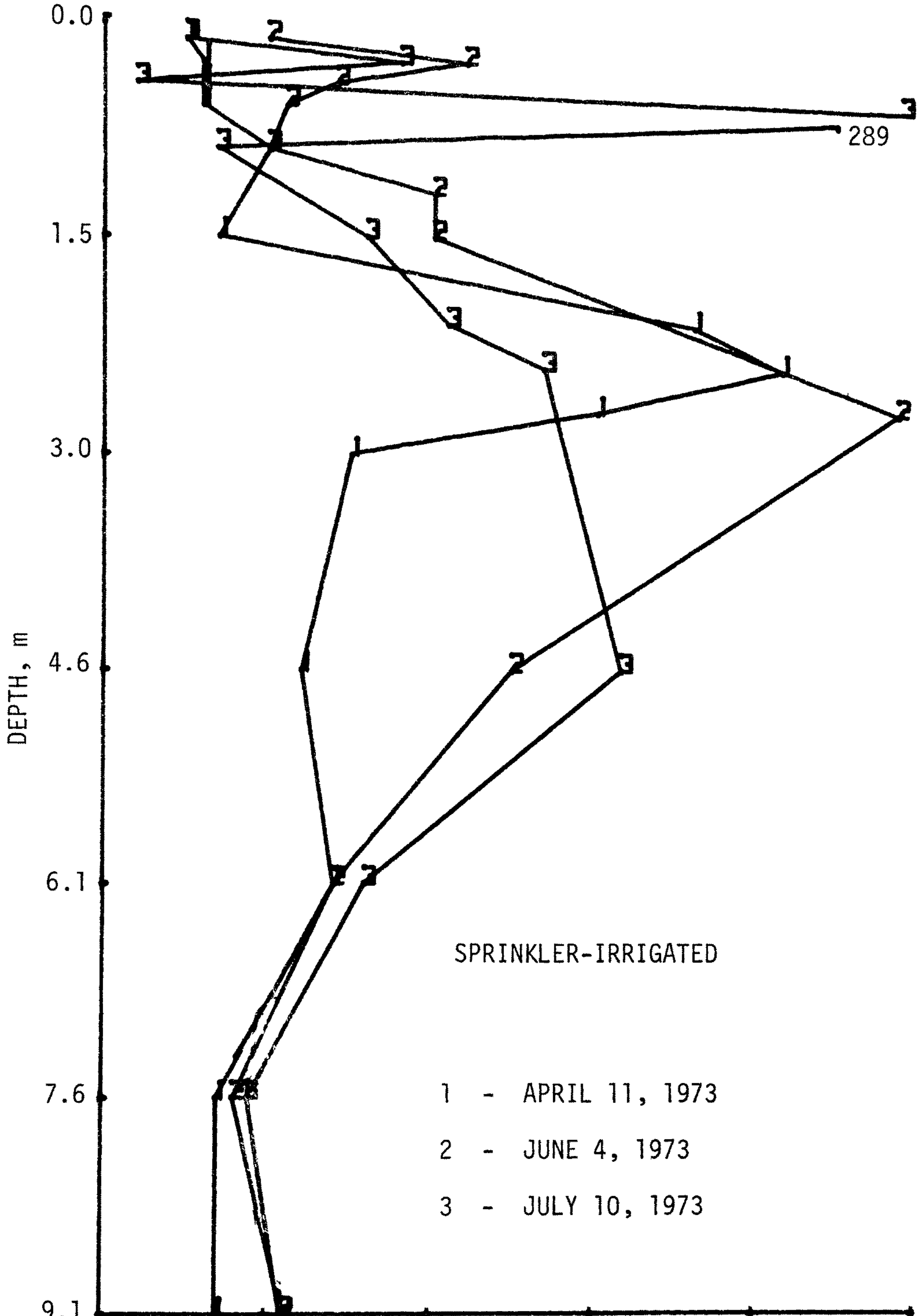


Figure 132. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a plot treated with sulfur-coated urea banded in the bed.

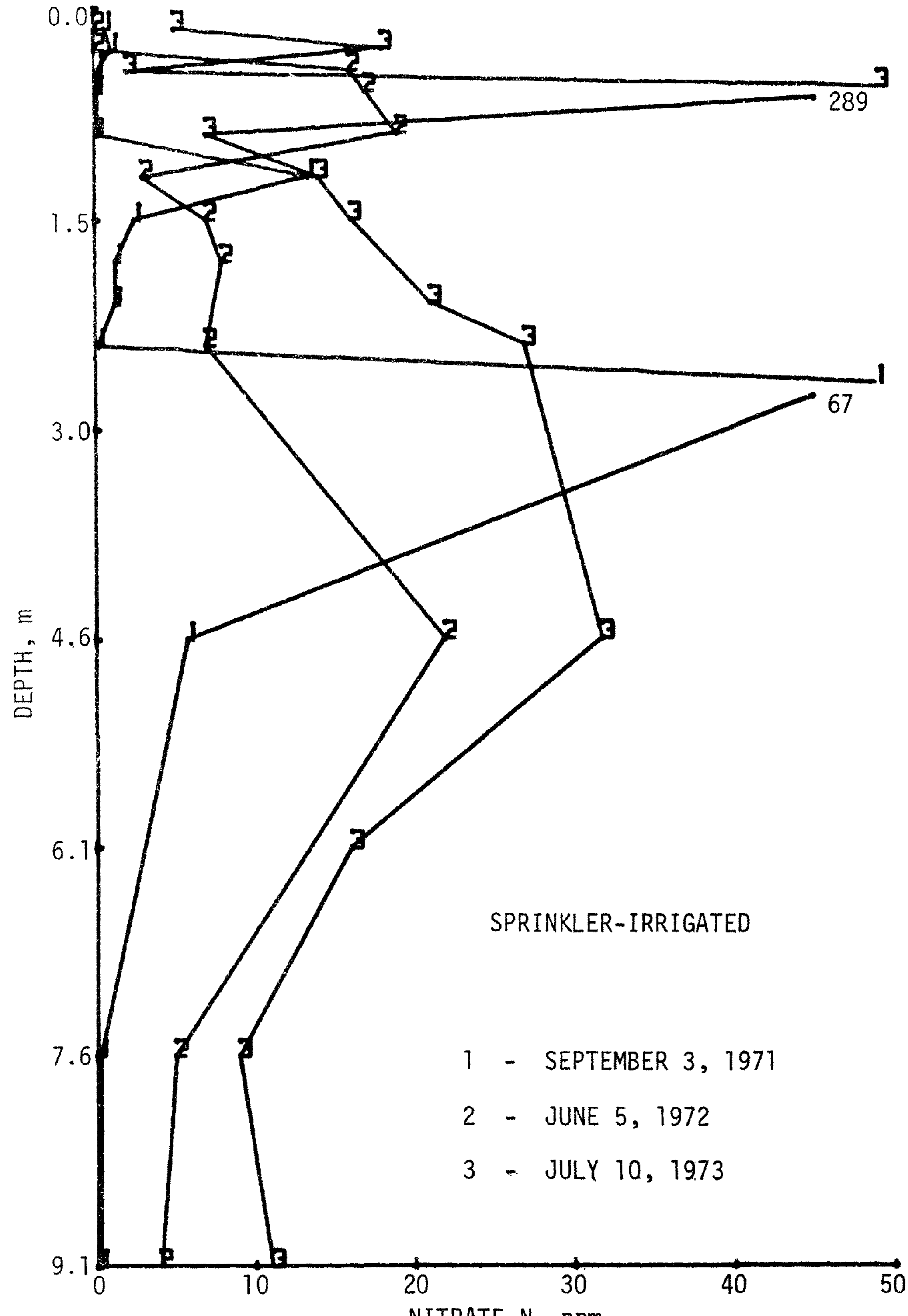


Figure 133. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with sulfur-coated urea banded in the bed.

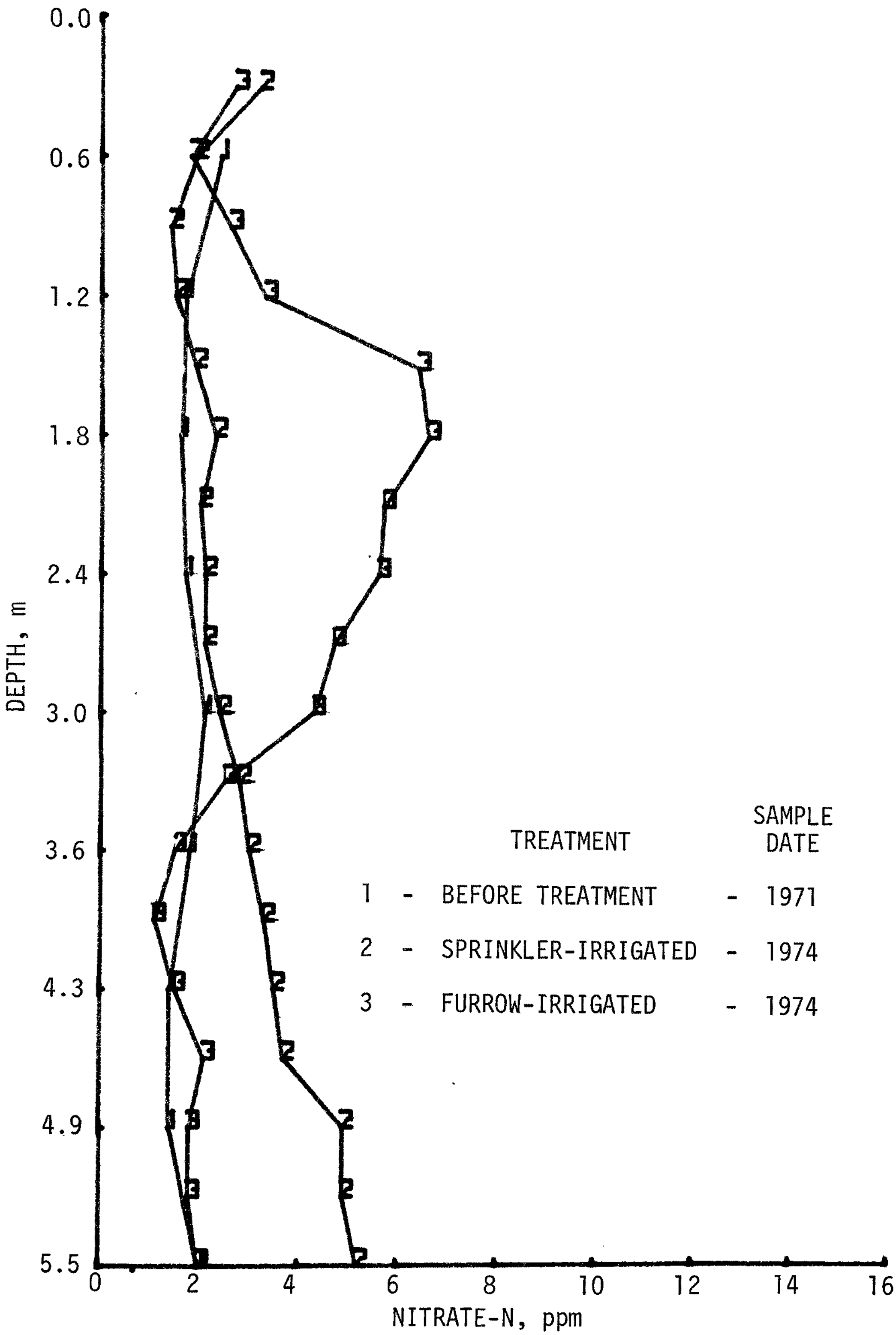


Figure 134. Soil extract (1:1) nitrate-N concentrations by soil depth before treatment (1971) and after four years of sulfur-coated urea application and irrigated by different systems, 1974. (Total N - 518 kg/ha)

deficiency in the surface which was corrected in 1973 by sidedressing at planting. These problems are expressed in the erratic yields obtained in 1971 and 1972 (Table 23). In 1973, when good quality seed were planted and the crop was sidedressed with a small amount of nitrogen, the yields were much higher and more consistent.

TABLE 23. YIELD AND IRRIGATION APPLICATION DATA OF TREATMENTS SPRINKLER-IRRIGATED BY DIFFERENT CRITERIA

	Criteria for irrigation					
	Visual		-20 cb potential		-40 cb potential	
	Water applied, cm	Yield, ears/ha	Water applied, cm	Yield, ears/ha	Water applied, cm	Yield, ears/ha
1971	25.40	24,710	38.10	27,799	22.86	13,590
1972	27.94	26,872	25.40	14,517	27.94	18,224
1973	26.42	47,876	25.53	53,126	20.32	47,875
Total (1971-3)	79.76	99,458	89.03	95,442	71.12	79,689
Avg. (1971-3)	26.57	33,153	29.68	31,814	23.71	26,563
Total (1972-3)	56.36	74,748	50.93	67,643	48.26	66,099
Avg. (1972-3)	27.18	37,374	25.46	33,821	24.13	33,049

There were some differences in the amount of water required where the different criteria were used. In 1971, more water was applied to the -20 cb than the visual and -40 cb treatments. In 1972 the reverse was true in that more water was applied to the visual and -40 cb treatments than the -20 cb treatments. The irrigation water applied to the visual and -20 cb treatments was approximately equal, and higher than the -40 cb plot in 1973. Rainfall amounts during the growing season for 1971, 1972 and 1973 were 23.34, 23.83 and 10.57 cm, respectively. It is interesting to note that the difference in irrigation water requirement between the -20 cb and -40 cb treatments in 1972 and 1973 (0.13 to 7.62 cm) was less than the difference in the growing season rainfall between the two years (13.16 cm).

With the exception of the 38.10 cm of irrigation water applied to the -20 cb plot when 7.62 cm was applied at each application, the maximum difference in water applied between all treatments was only 7.62 cm (20.32 to 27.94 cm). There were no major differences in yields due to irrigation criteria in 1973 when major production problems did not occur. It thus appears that there is no significant difference among the various criteria used relative to yield and the amount of irrigation water required if the producer has the capability to apply water equal to the ET.

Few differences in nitrate movement were observed in plots irrigated by the various criteria (Figures 135, 136, and 137). Initially (July 8, 1971),

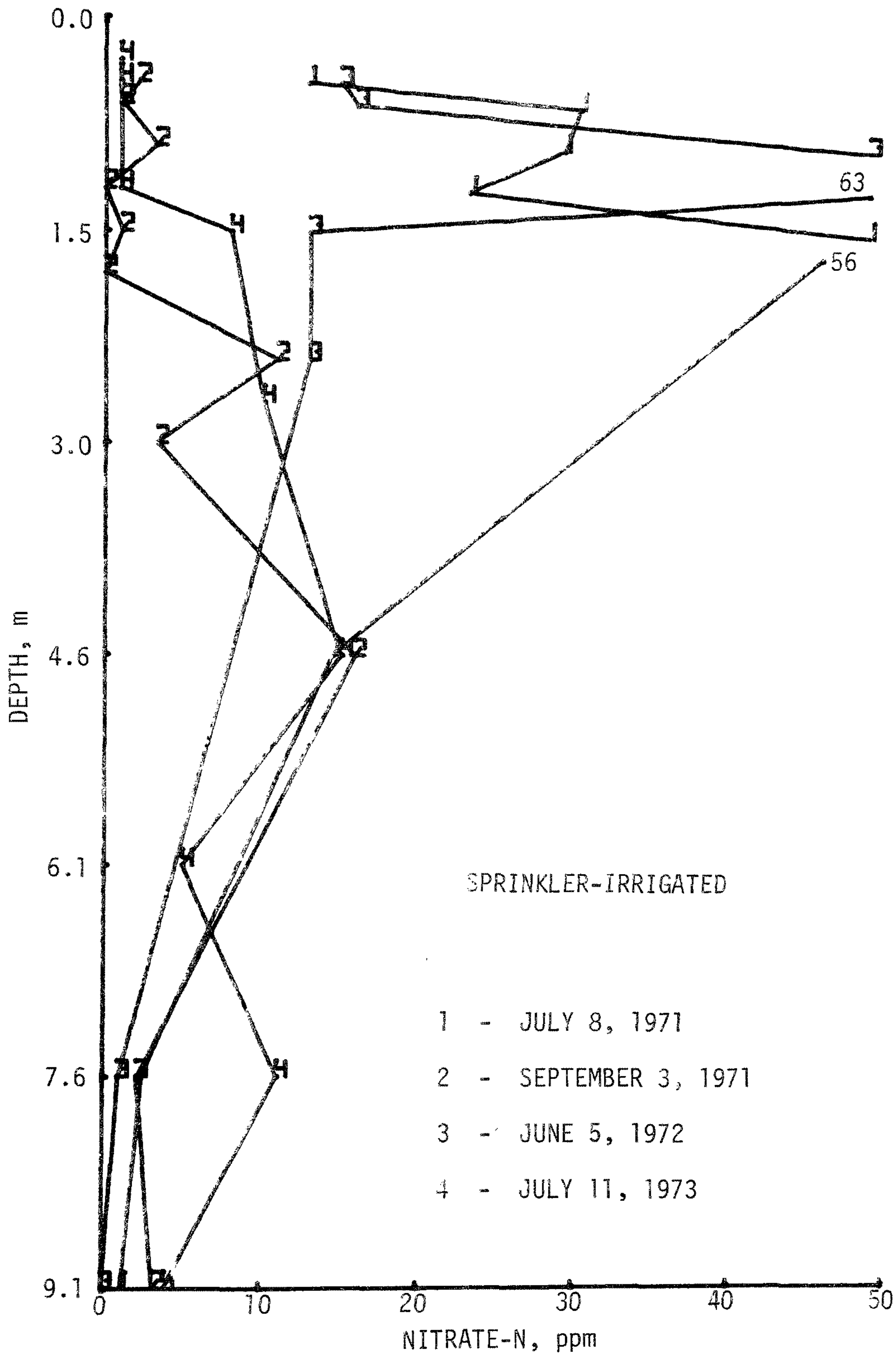


Figure 135. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with Uran banded in the bed and irrigated when significant leaf curl occurred.

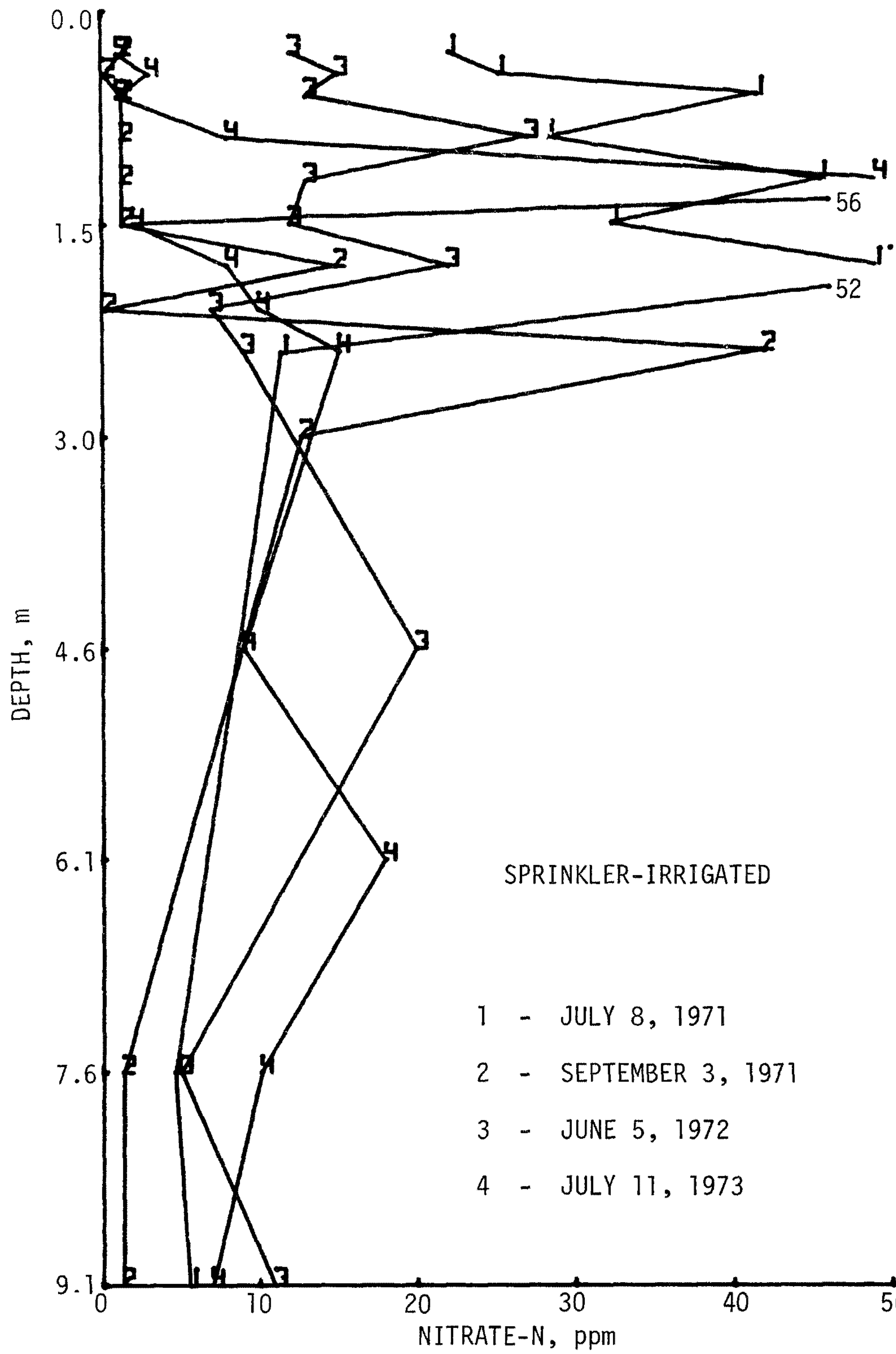


Figure 136. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with Uran banded in the bed and irrigated when the tensiometer reached -20 cb potential.

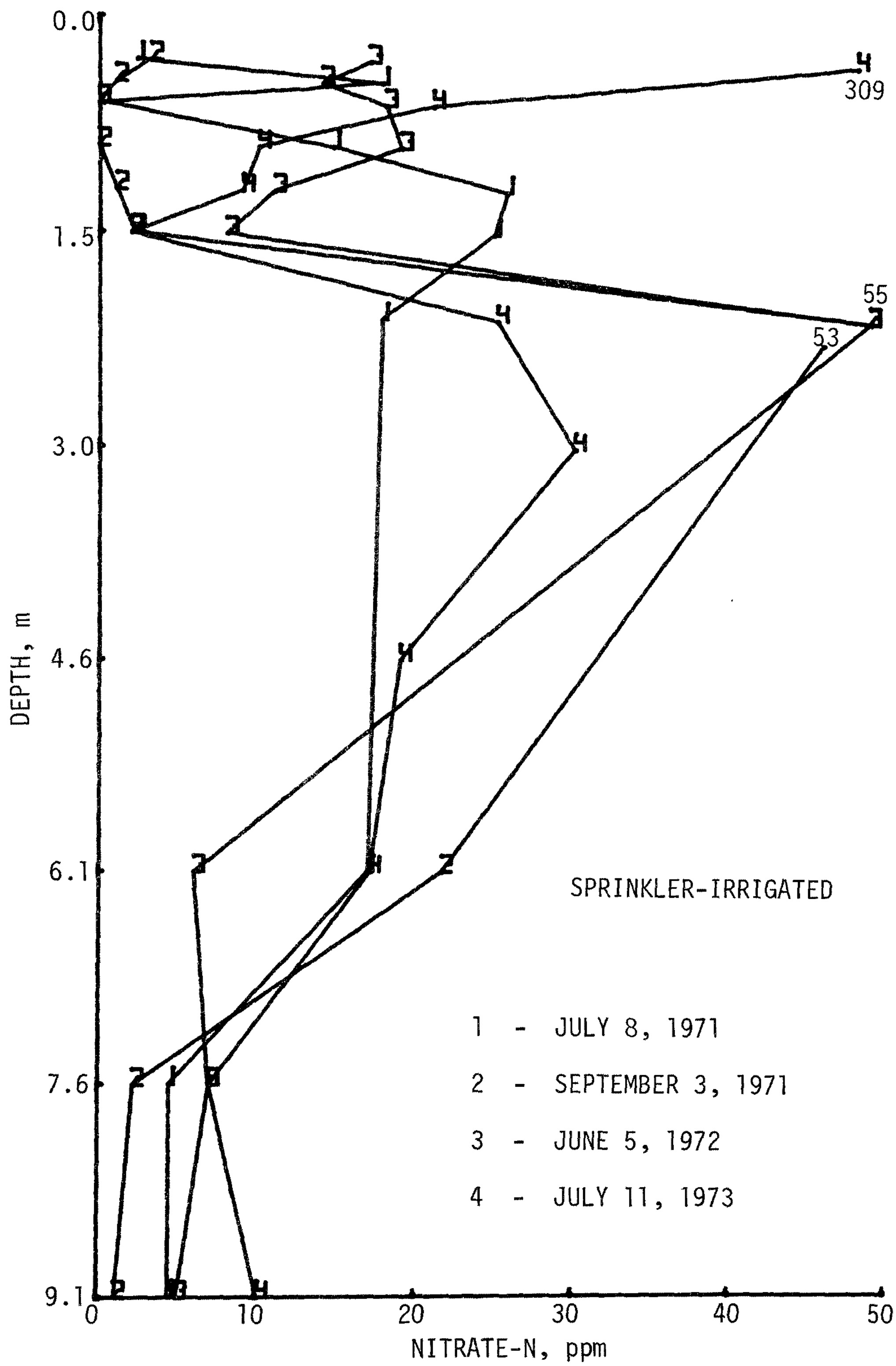


Figure 137. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with Uran banded in the bed and irrigated when the tensiometer reached -40 cb potential.

the profile of the visual and -20 cb plots was higher in nitrate-N in the root zone (0 to 1.5 cm) than the -40 cb plot. From 1.5 to 6.1 m, the -40 cb plot had higher nitrate-N levels in the soil-water extracts than the other two treatments. At the end of the study, the -20 and -40 cb plots had higher concentrations of nitrate-N than the leaf curl criteria. Below 6.1 m there was little difference among treatments.

Summary

Nitrate-N from soil-water extracts where ammonia and Uran were applied in the bed was much higher in the root zone (0 to 1.5 m) than where ammonia was applied below the water furrow indicating the fertilizer was better located to be utilized. Nitrate-N was less in the plots where Uran was banded in the bed than in the unfertilized plots in the sprinkler irrigation system. Banding fertilizer in the bed appears to be superior to banding fertilizer below the water furrow from the standpoint of maintaining high nitrate-N levels in the root zone.

In the plots fertilized with sulfur-coated urea, nitrate-N values were low in the furrow-irrigated plot but high in the sprinkler-irrigated plot for some unexplained reason. No advantage was obtained from treating with ammonia + N-Serve over ammonia alone.

Thus, it appears that if conditions are adequate to produce a good corn crop, it makes little difference if the criteria used for applying water is leaf curl, or -20 to -40 cb potential. No significant differences existed below 6.1 m in the amount of nitrate-N in the porous bulb sample where the amount of water added was estimated by a combination of potential ET and leaf area.

OBJECTIVE 3 - POTENTIAL OF USING SUBIRRIGATION FOR MORE EFFICIENT WATER APPLICATION AND NEW SYSTEMS OF FERTILIZATION FOR LONG-RANGE SOLUTIONS TO THE POLLUTION PROBLEM

Porous Bulb Samples

As previously discussed, some increases in nitrate-N concentrations were noted during the 1973 growing season in the sprinkler-irrigated (Figures 90 and 93) and furrow-irrigated (Figures 91, 92, and 94) unfertilized plots. Such major differences were not noted in the manual subirrigated (Figure 138) or the automatically-subirrigated (Figure 139) unfertilized plots. In general, the values were 15 ppm or less throughout the profile in both systems.

No increases in nitrate-N in the porous bulb extracts from the control plots in the subirrigation systems were noted between 1971 and 1973. In a manually-subirrigated control plot (Figure 140), the nitrate-N of soil-water extracts in 1973 were approximately equal to those obtained in 1971. In a similar automatically-subirrigated plot (Figure 141), the nitrate-N content of the soil-water extracts on June 4, 1973 was significantly less than the values obtained on July 5, 1972. Problems were experienced in obtaining extracts from some of the automatically-subirrigated plots due to the small

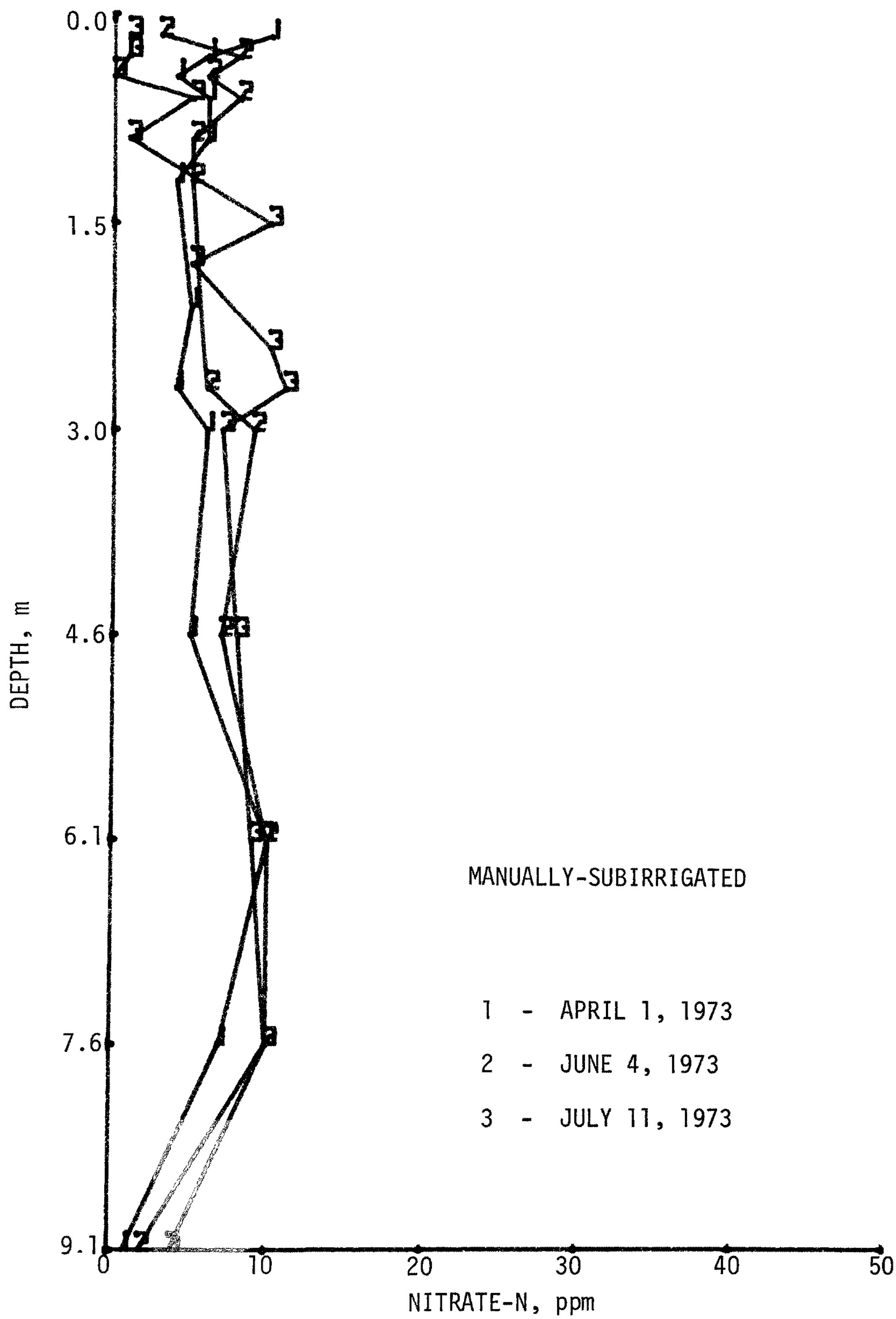


Figure 138. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a control plot.

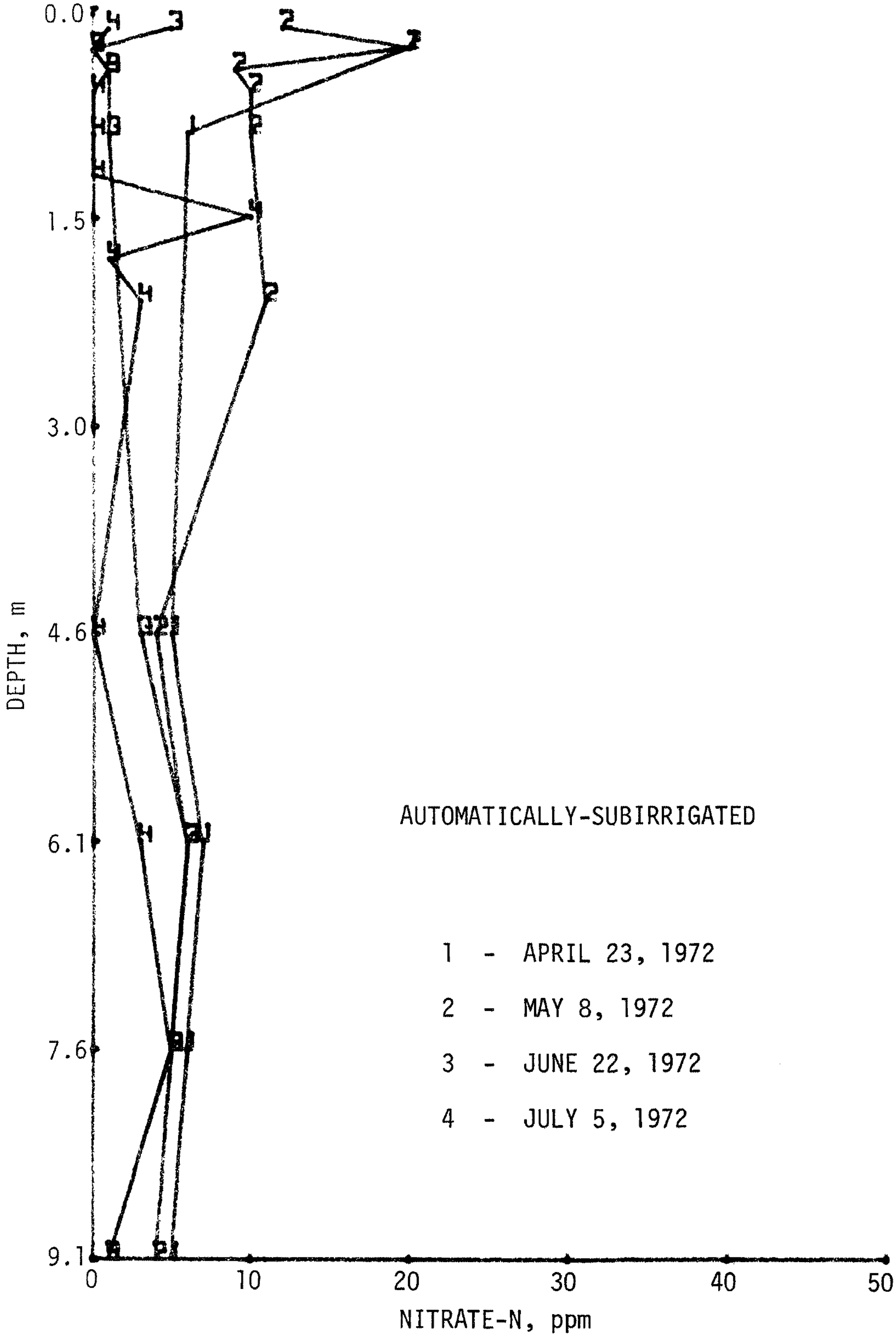


Figure 139. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1972 for a control plot.

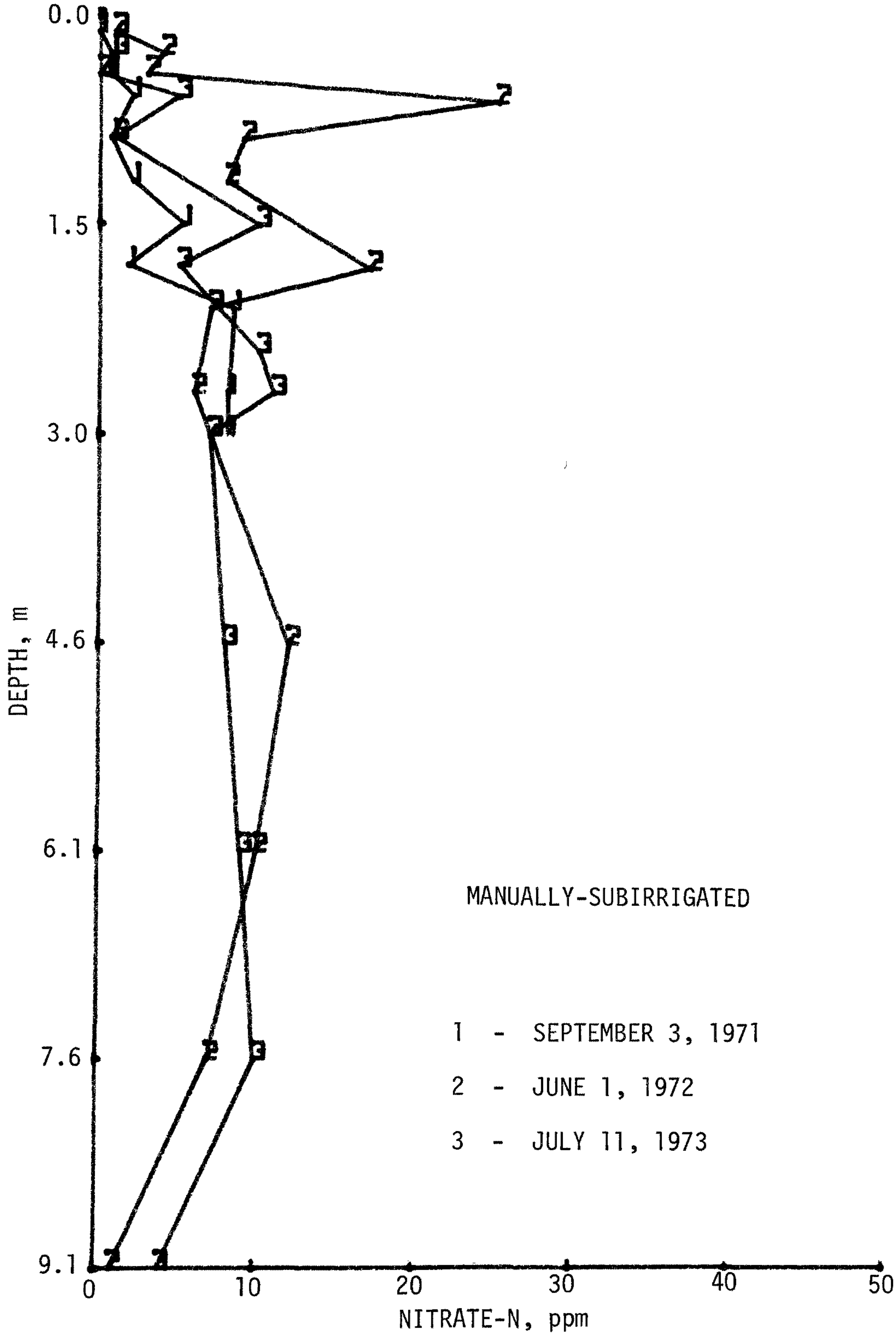


Figure 140. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a control plot.

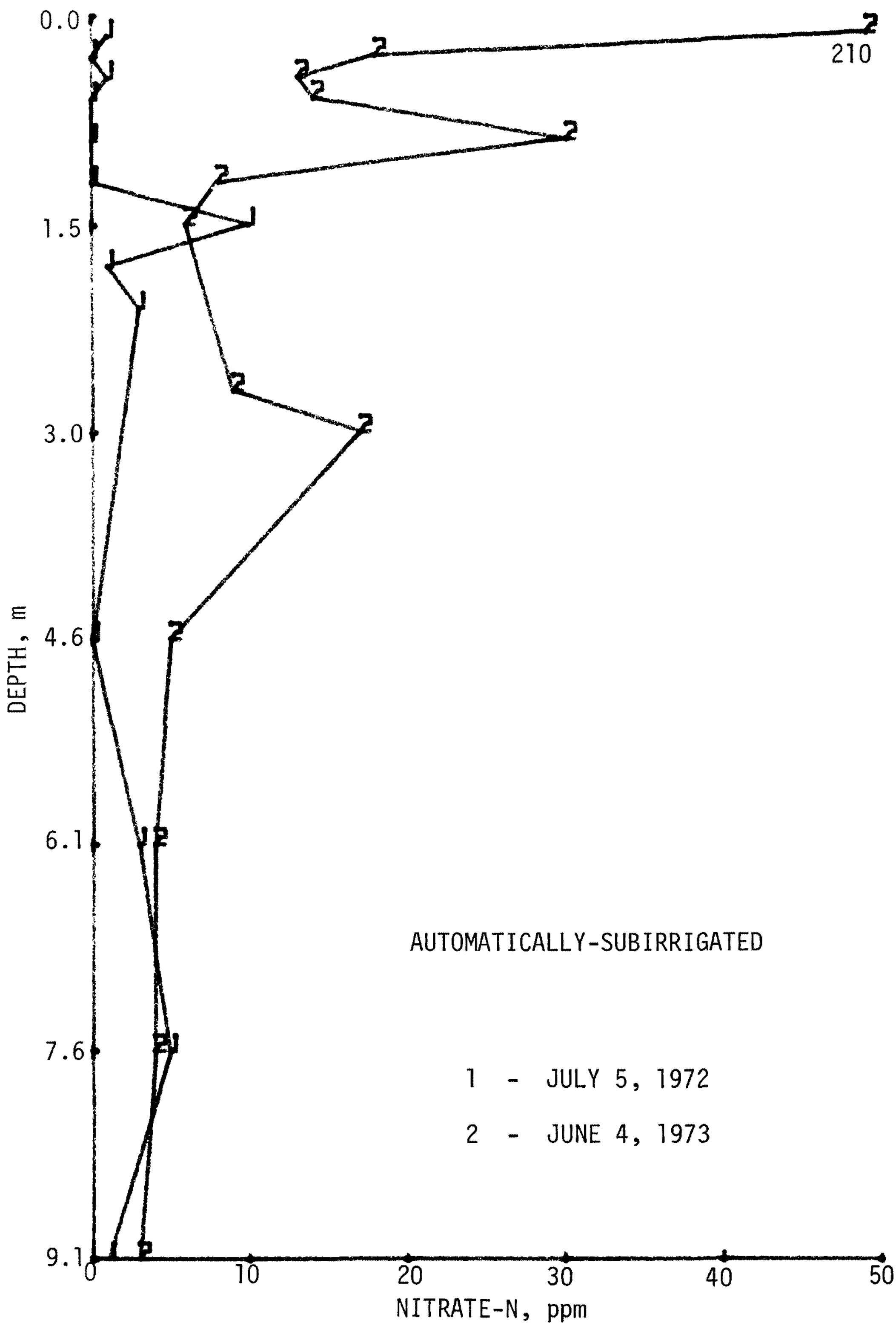


Figure 141. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1972-1973 for a control plot.

amounts of water applied, and it was not possible to compare soil-water extracts from the ends of both growing seasons. Therefore, the data from 1973 were obtained in the early part of the growing season when the nitrate-N content was rather high due to nitrification from soil nitrogen. However, no increases were noted in the nitrate-N of the soil-water extracts below 4.6 m.

Due to the unique method of applying water in the root zone by subirrigation systems, the obvious method of applying fertilizers would be through the system itself. When Uran was applied through both the manual (Figure 142) and automated (Figure 143) subirrigation systems in 1972 or 1973, two things were noted. High nitrate-N levels existed during the growing season in the root zone under both systems compared to the unfertilized plots of both systems (Figures 138 and 139). Also, higher nitrate-N concentrations were obtained in samples obtained below the root zone (>1.5 m) in the plots where fertilizer was applied through the irrigation water (Figures 144 and 145) than in the unfertilized plots (Figures 140 and 141) and the concentrations increased over the two-year period. The data thus suggest that, although the technique is efficient relative to maintaining high levels of nitrate-N in the root zone, much care must be taken relative to placement of the subirrigation system and applying the fertilizers to insure that the fertilizer is applied at the location and in the amount that can be absorbed by the crop so that little nitrate-N remains to be lost to irrigation return flow.

Figure 146 shows the nitrate-N concentration of the soil-water extracts where anhydrous ammonia was banded in the bed over the manual subirrigation system in 1973. The concentrations in the root zone were higher on June 4 in the fertilized plot (Figure 146) than the unfertilized plot (Figure 138). Concentrations below the root zone (>1.5 m) in the fertilized plot were higher in April and June and the same in July at the end of the growing season than those in the unfertilized plot. Between 1971 and 1973, concentrations in the ammonia-fertilized plot (Figure 147) were slightly lower in the root zone (<1.5 m) and slightly higher below the root zone (>1.5 m) than the unfertilized plot (Figure 140).

Uran was applied in the bed in both the manual subirrigation system and automated subirrigation system. The data from the 1972 and 1973 growing seasons are similar to those obtained from other fertilizer treatments. For the manual subirrigation system (Figure 148), nitrate-N concentrations of the soil-water extracts were high in June but low in July at the end of the season similar to the plot fertilized with anhydrous ammonia (Figure 146). Concentrations of nitrate-N in the root zone of the automated subirrigation plot (Figure 149) were similar to those of the unfertilized plot (Figure 139). Below the root zone, the concentrations of nitrate-N were higher in the Uran-fertilized plot (Figure 149) than in the unfertilized plot (Figure 139). Between 1971 and 1973 there was a trend toward an increase in the nitrate-N in the soil-water extracts between 3.0 and 6.1 m in the Uran-fertilized subirrigated plots (Figures 150 and 151) as compared to the unfertilized plots of the same systems (Figures 140 and 141). However, since the differences are only 3 to 8 ppm nitrate-N, conclusions cannot be made concerning their significance.

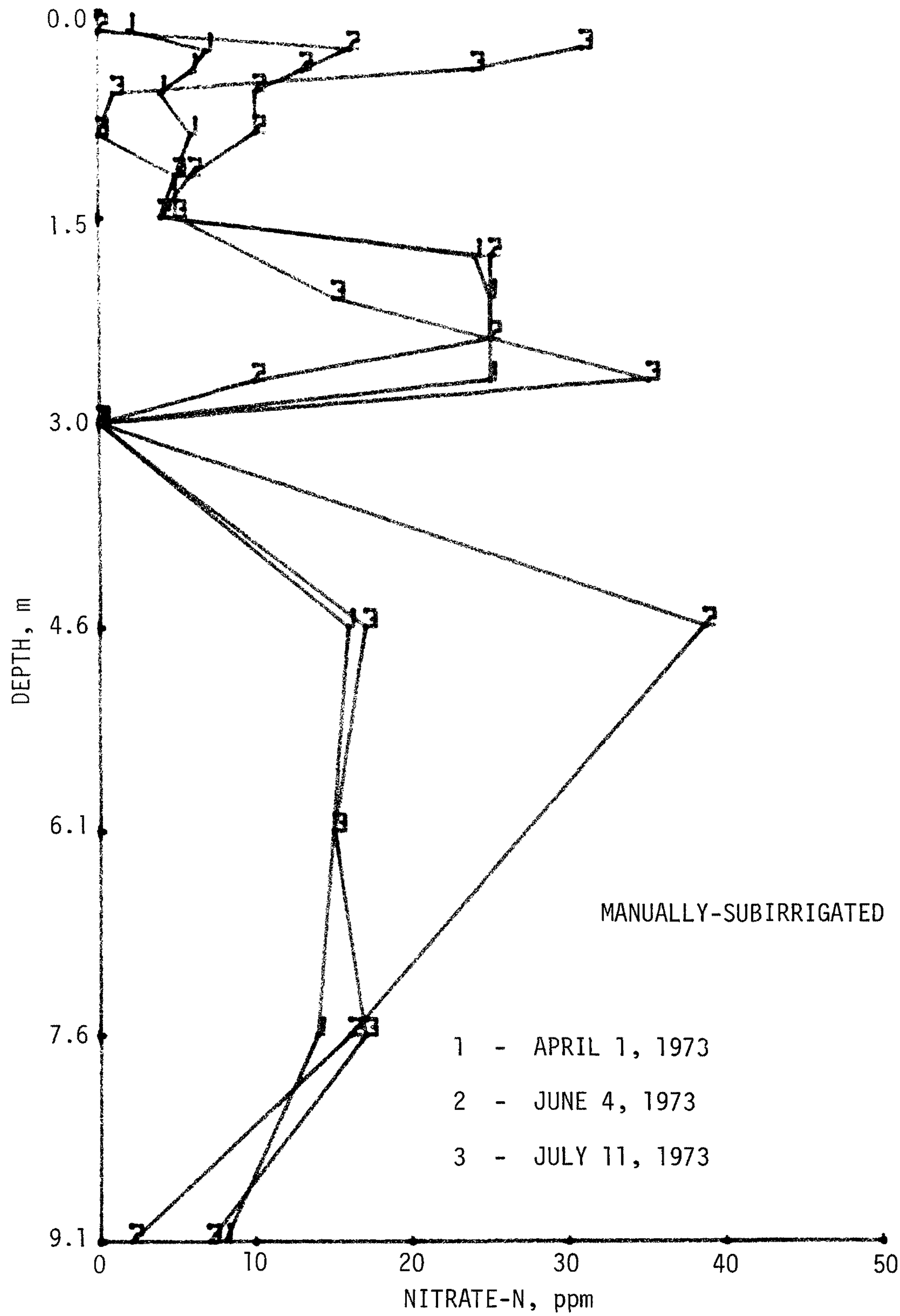


Figure 142. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a plot treated with Uran applied in the irrigation water.

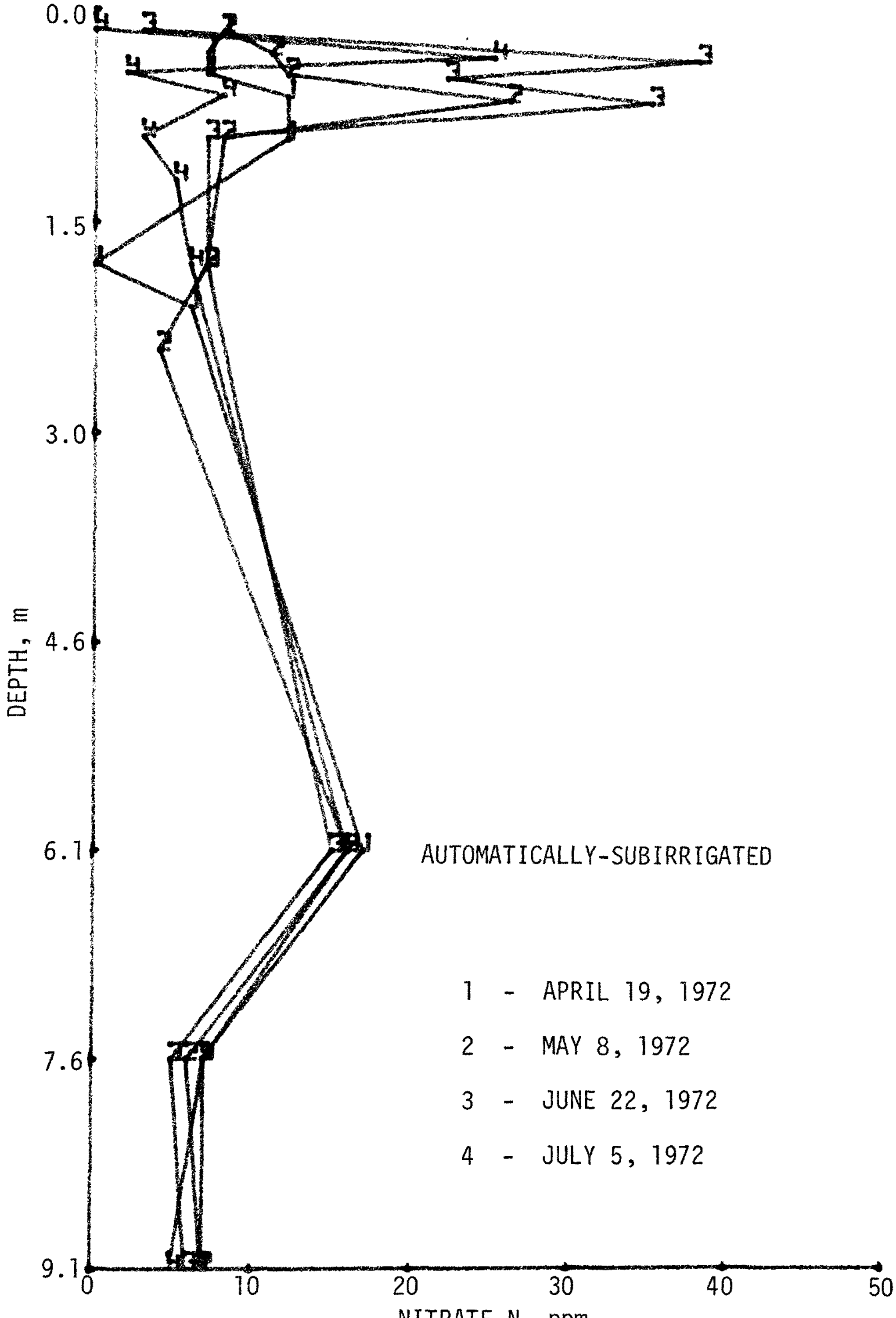
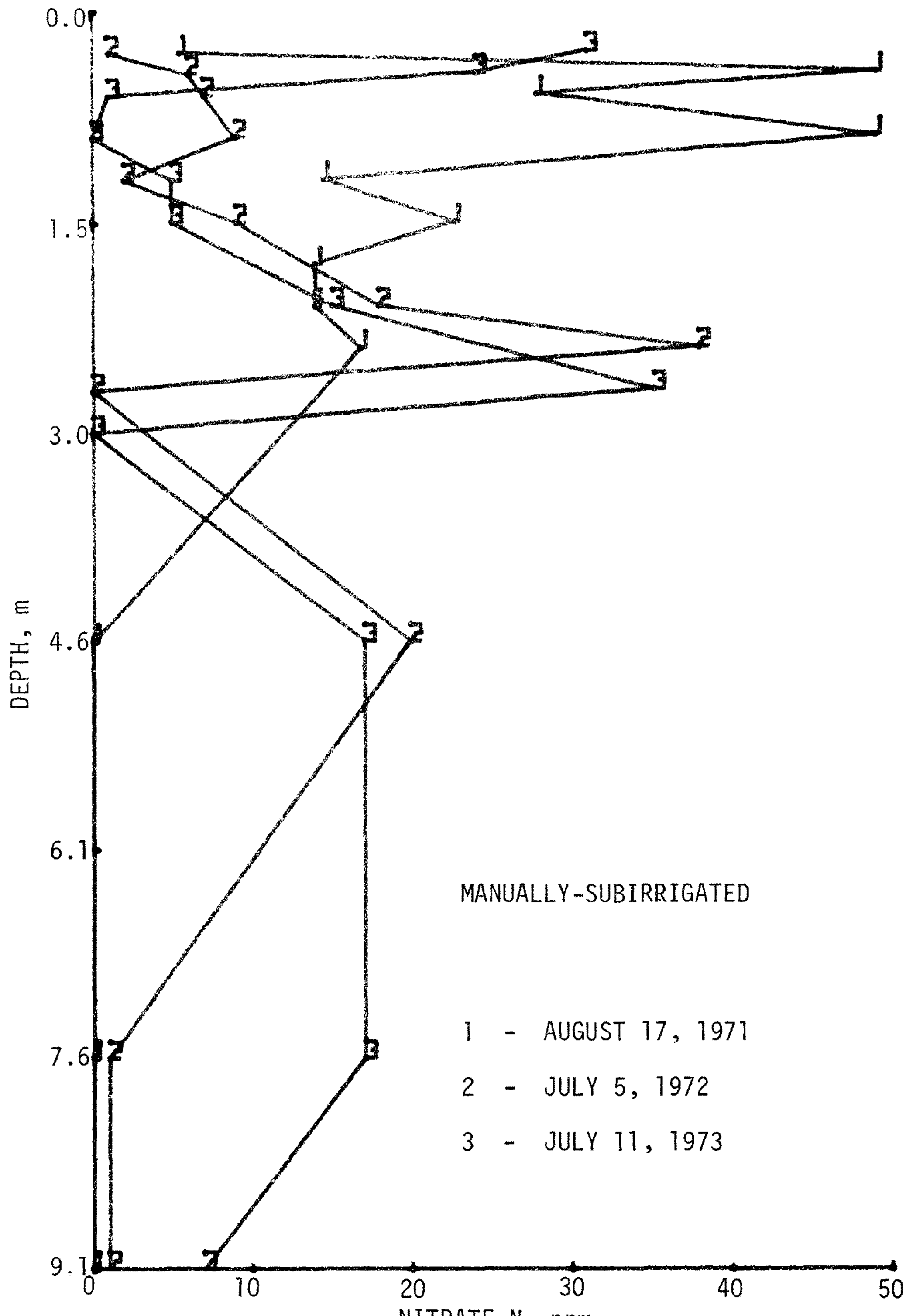


Figure 143. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1972 for a plot treated with Uran applied in the irrigation water.



igure 144. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with Uran applied in the irrigation water.

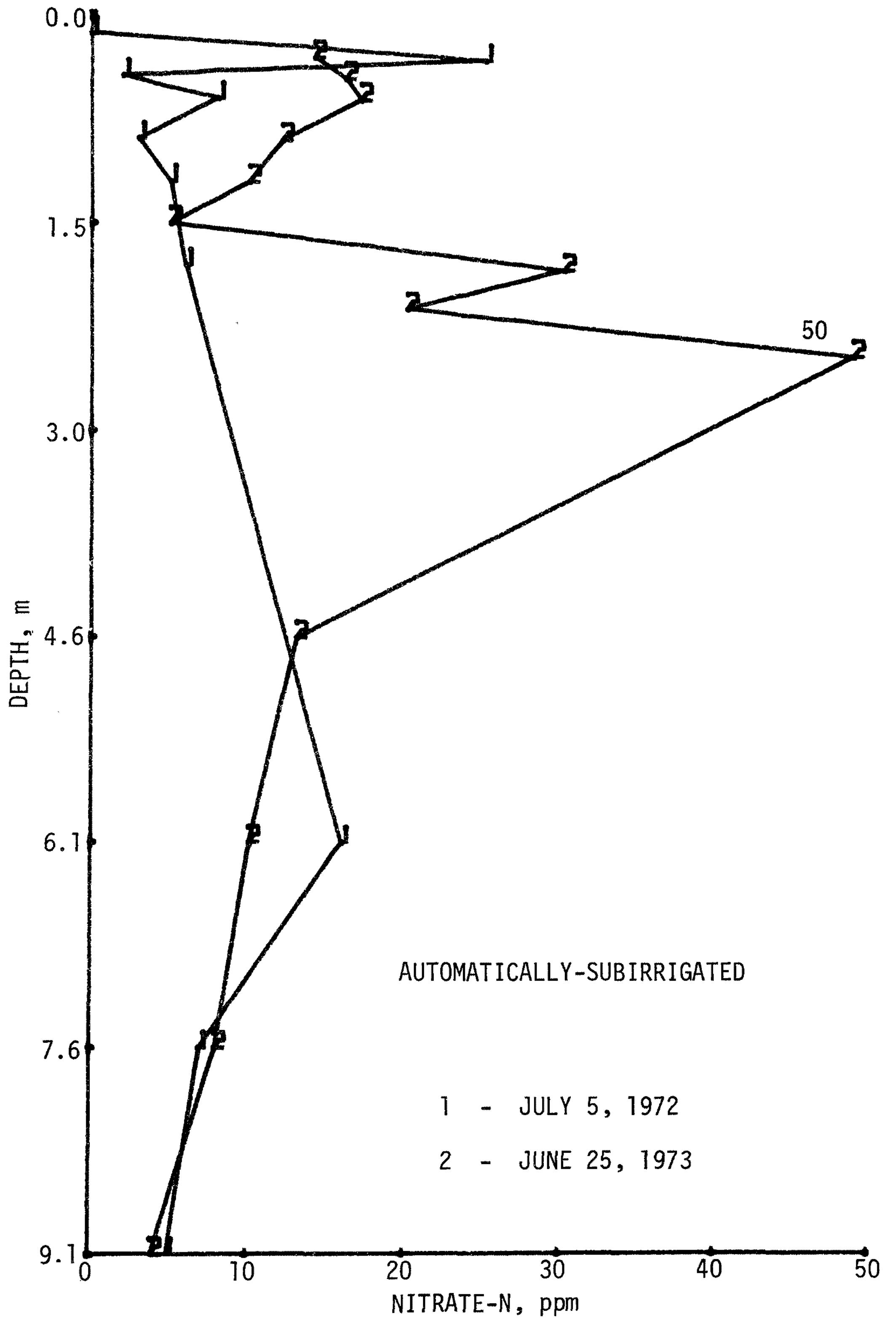


Figure 145. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1972-1973 for a plot treated with Uran applied in the irrigation water.

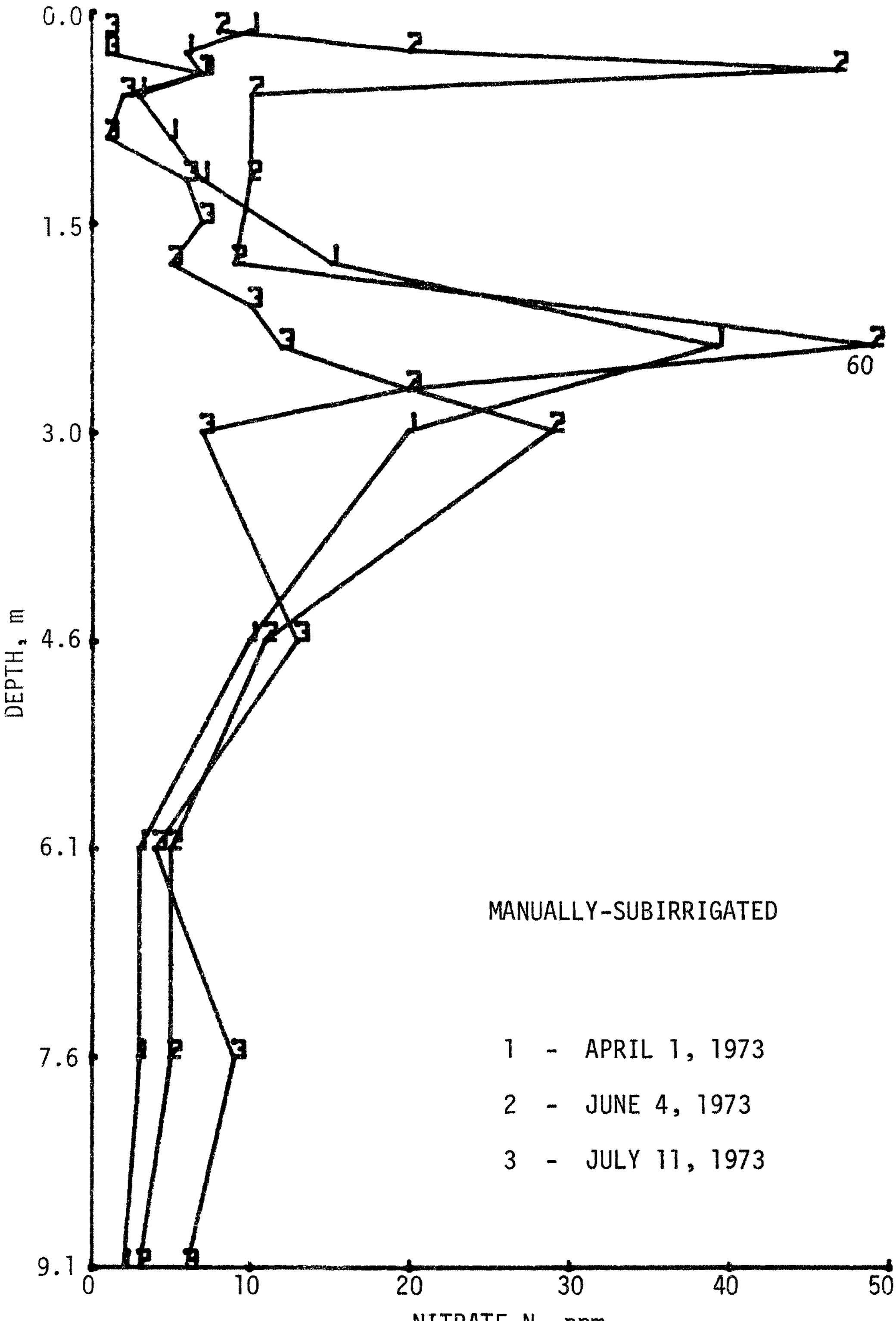


Figure 146. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a plot treated with ammonia banded in the bed.

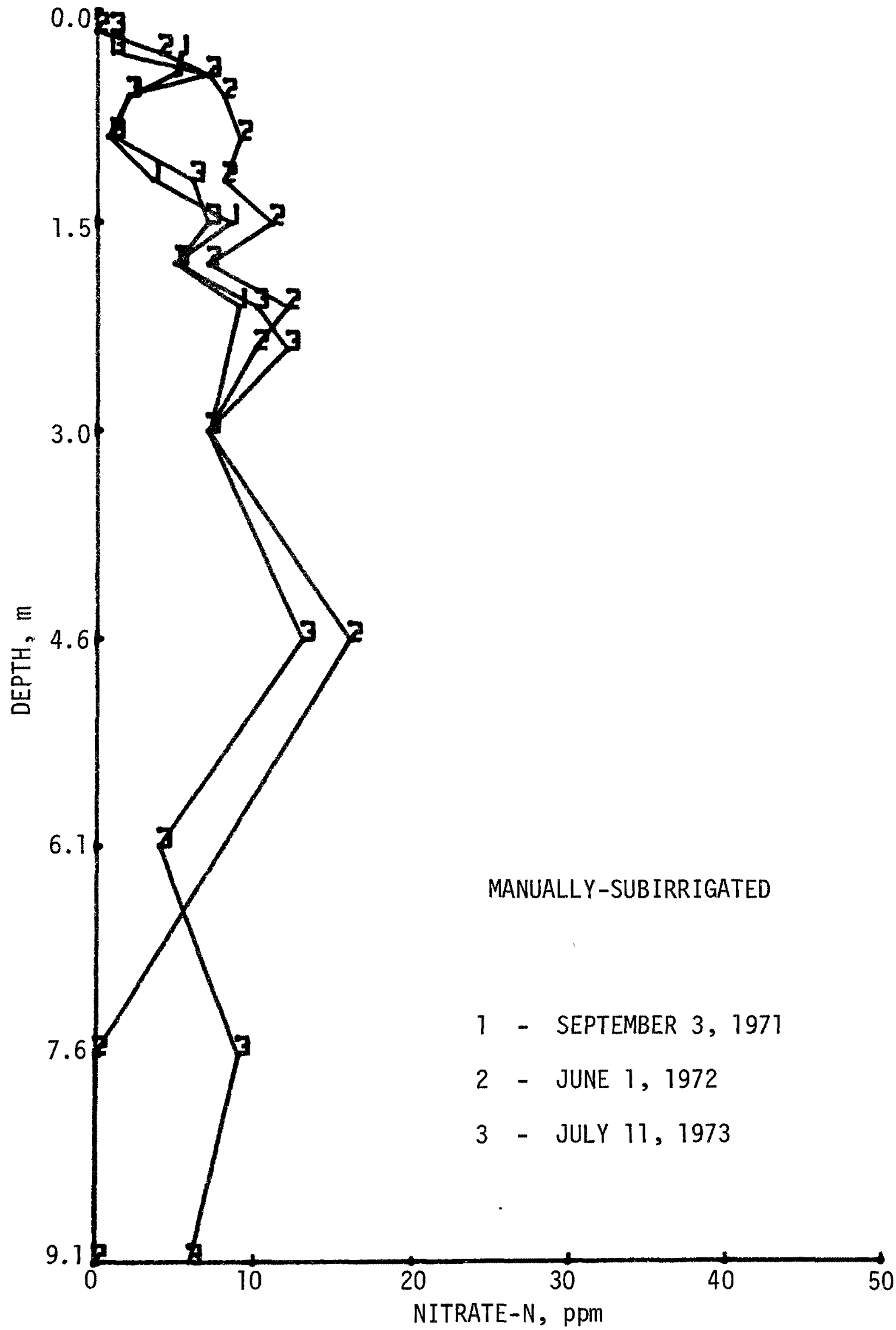


Figure 147. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with ammonia banded in the bed.

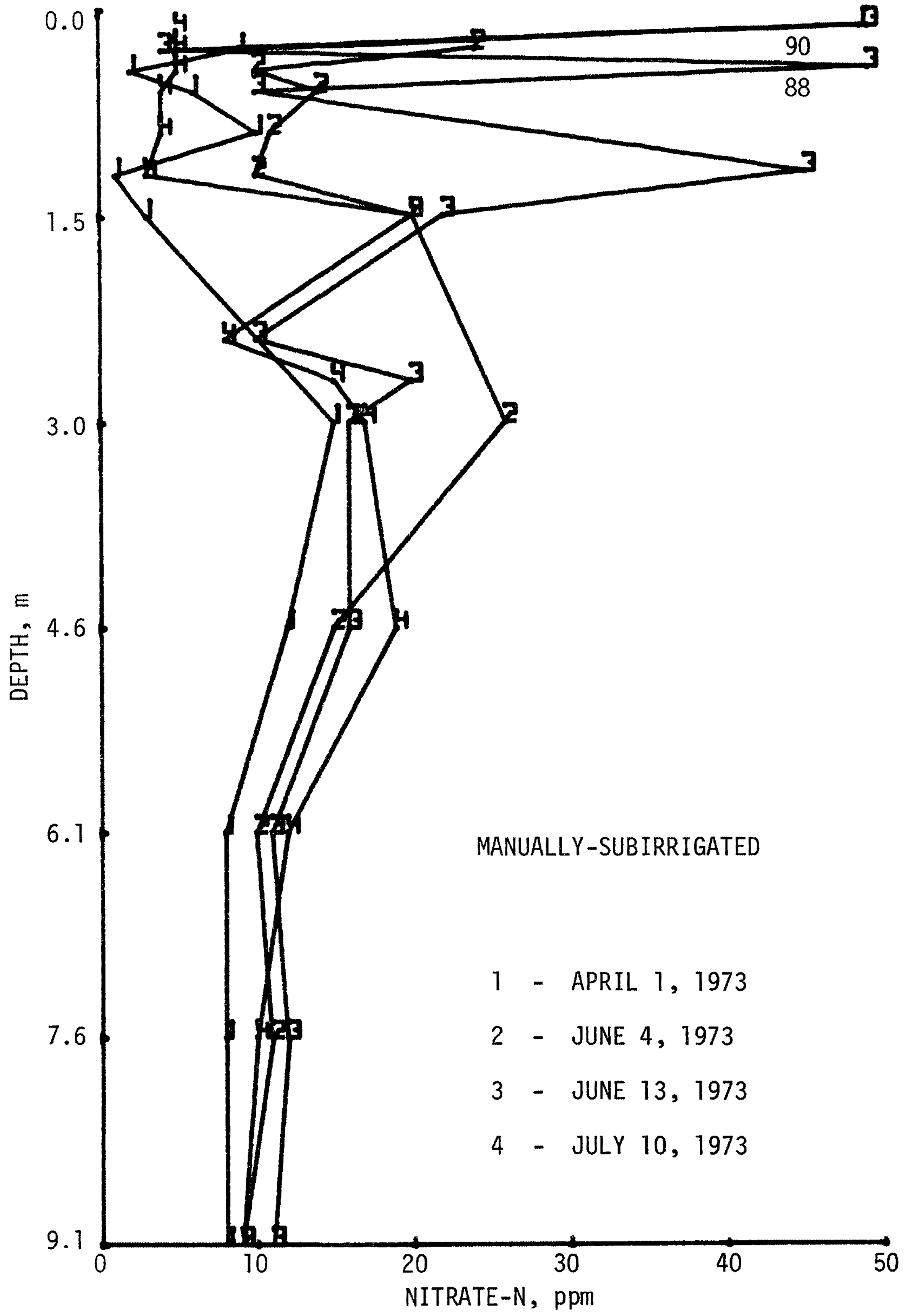


Figure 148. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a plot treated with Uran banded in the bed.

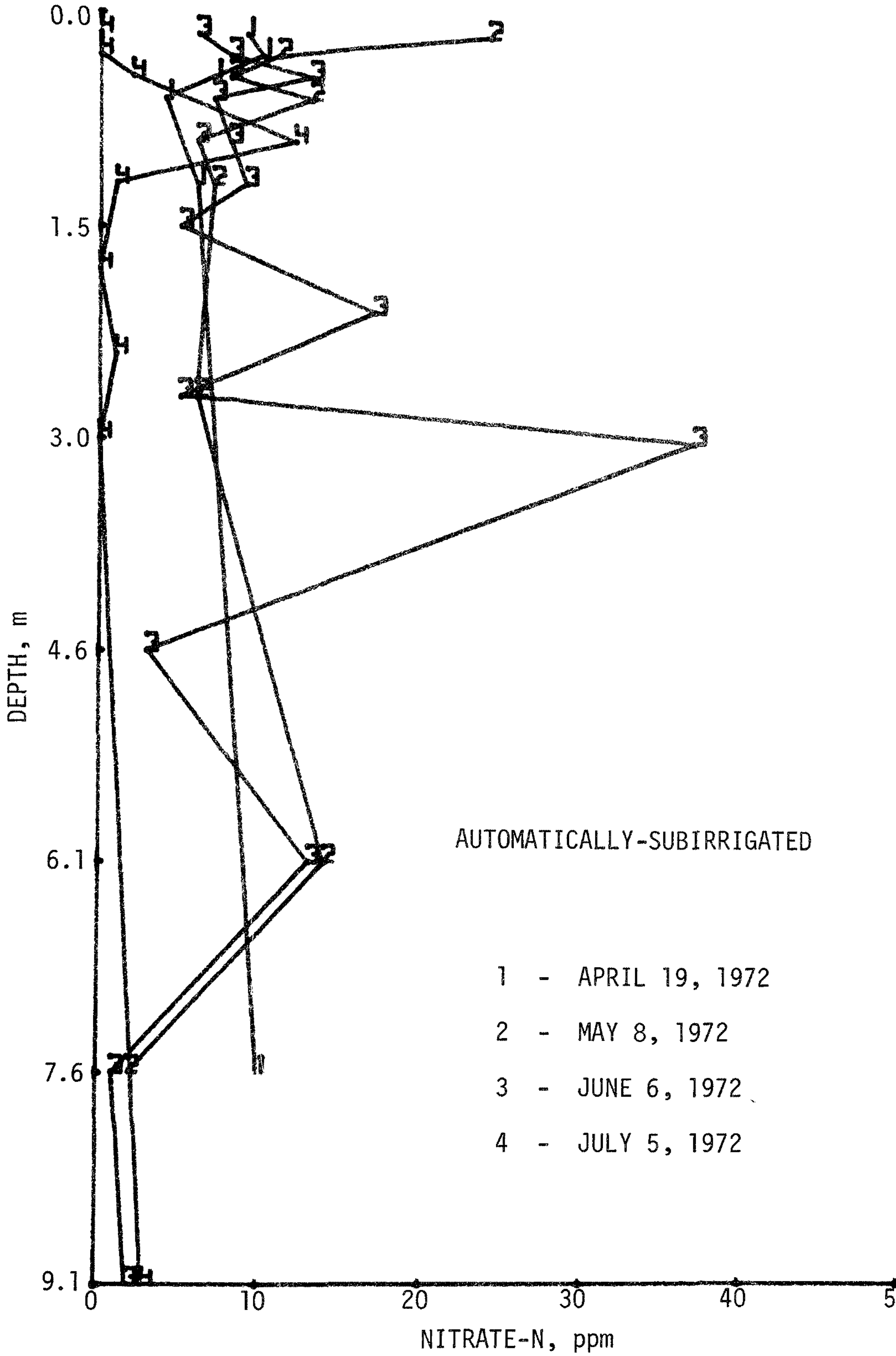


Figure 149. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1972 for a plot treated with Uran banded in the bed.

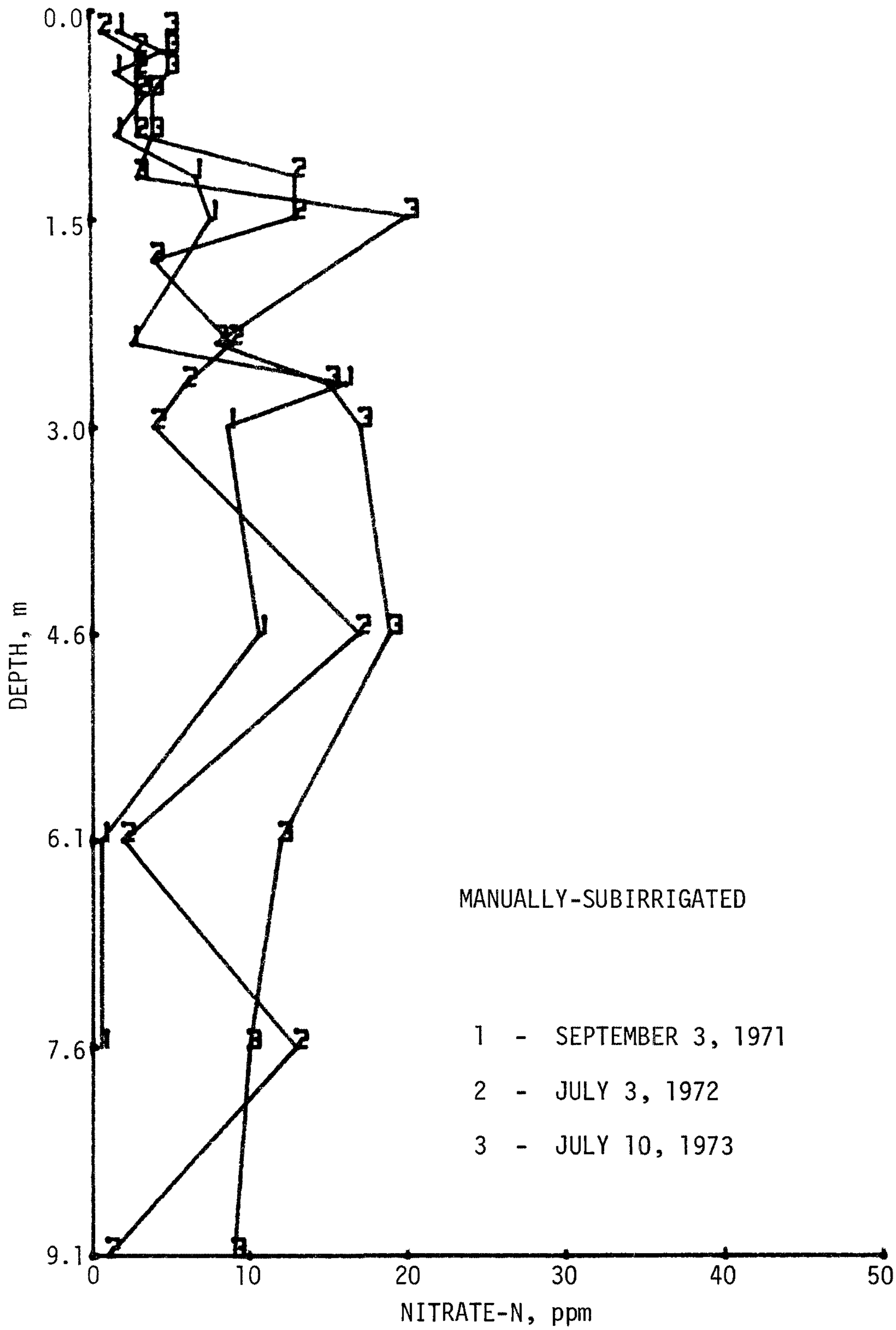


Figure 150. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with Uran banded in the bed.

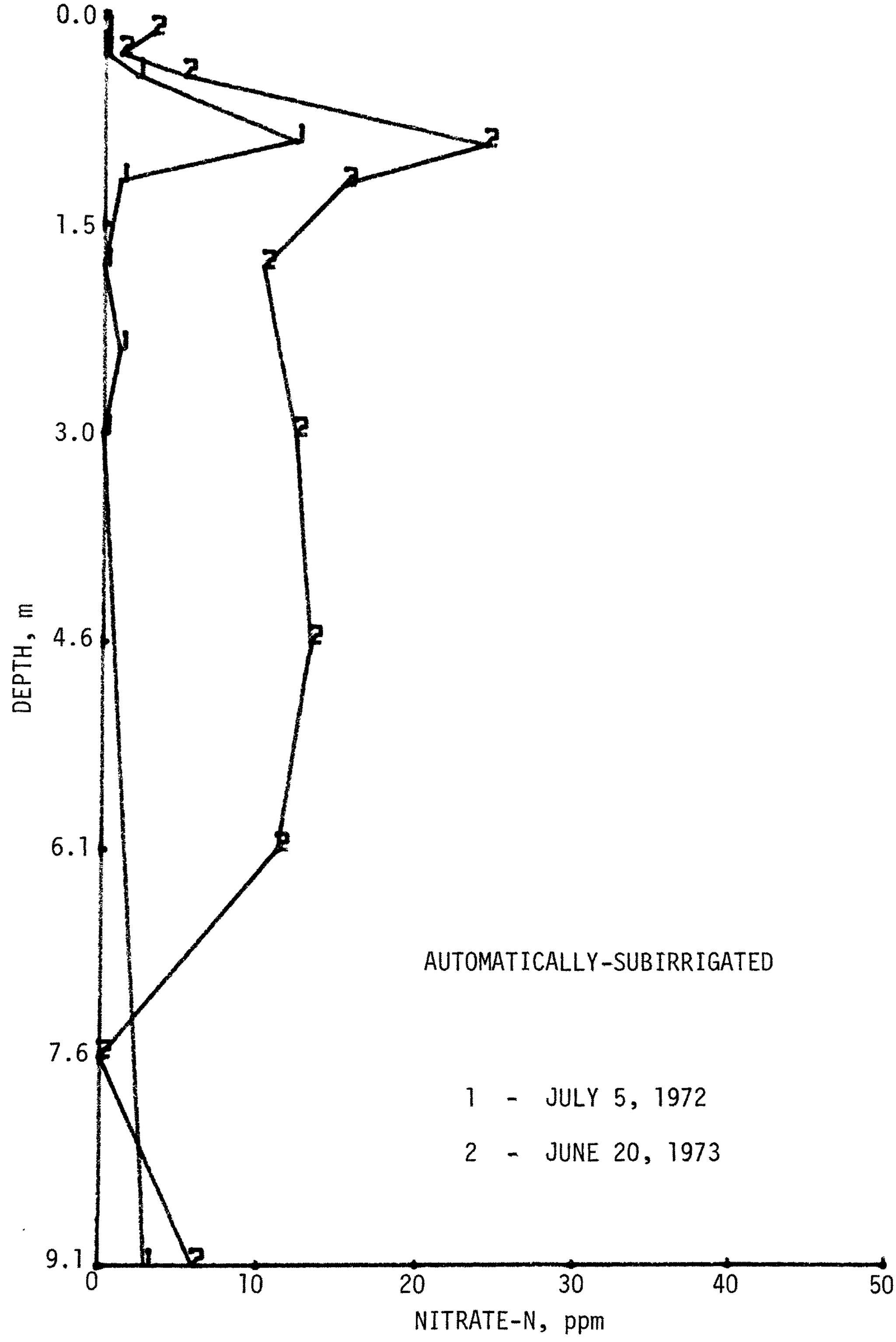


Figure 151. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1972-1973 for a plot treated with Uran banded in the bed.

Nitrate-N content of the soil-water extracts where urea was banded in the manual subirrigation plots (Figure 152) was only slightly higher than the unfertilized plot (Figure 138) at 0 to 1.2 m. The major difference between the two plots was the higher values for nitrate-N between 1.5 and 3.0 m which was below the root zone. The same was true between 1971 and 1973 for the two treatments (Figures 153 and 140). There was little difference between the two treatments in the nitrate-N concentration below 3.0 m.

Ammonia + N-Serve (Figure 154) was compared to ammonia alone (Figure 155) during 1971. It can be seen that the N-Serve did not significantly decrease the rate at which ammonia was converted to nitrate (Figure 154) when compared to the ammonia alone (Figure 155) or the unfertilized plot (Figure 138). As previously mentioned, treatments containing N-Serve were discontinued after the 1971 growing season.

In summary, highest values for nitrate-N in porous bulb extracts in the root zone were obtained when Uran was applied with the irrigation water. However, significant increases in nitrate-N were also noted below the root zone indicating that discretion should be practiced relative to the placement of the irrigation pipe and the timing and amounts of Uran applied to insure that little nitrate remains to contribute to irrigation return flow.

With the exception of a few dates, nitrate-N concentrations where the various fertilizers were banded in the bed were only slightly higher than the unfertilized plots. It was not possible to account for much of the banded fertilizer.

Soil Samples

Average concentrations of nitrate-N found in 1:1 soil-water extracts of soil samples taken at five locations laterally across the beds and down to a depth of 6 m are shown for anhydrous ammonia, band application of Uran and band application of sulfur-coated urea in Figures 156, 157, and 158, respectively. These soil samples were taken in July of 1974 after four cropping years, and the data obtained from the extracts are plotted against the same type of extract from soil samples taken in 1971. The total amount of nitrogen applied as anhydrous ammonia was 514 kg of N/ha over the cropping period. The total amount of nitrogen applied as Uran was 508 kg/ha and 518 kg/ha as sulfur-coated urea. The amounts of nitrate-N found in the 1:1 soil extracts at depths below 1.5 m were generally less than those found in 1971 where anhydrous ammonia and sulfur-coated urea were used as the sources of nitrogen. This is in direct contrast to the data shown for ammonia (Figure 118), Uran (Figure 122), and sulfur-coated urea (Figure 134) applications made to furrow and sprinkler systems where increases in nitrate-N concentrations in the soil profile were evident. There was some increase in nitrate-N in the soil where Uran was banded as the source of nitrogen, and the pattern exhibited is somewhat similar to that seen under sprinkler and furrow irrigation.

In summary, the low nitrate data obtained from soil samples show that subirrigation used in conjunction with banding fertilizer applications above the subirrigation lateral has some potential for reducing pollution hazards.

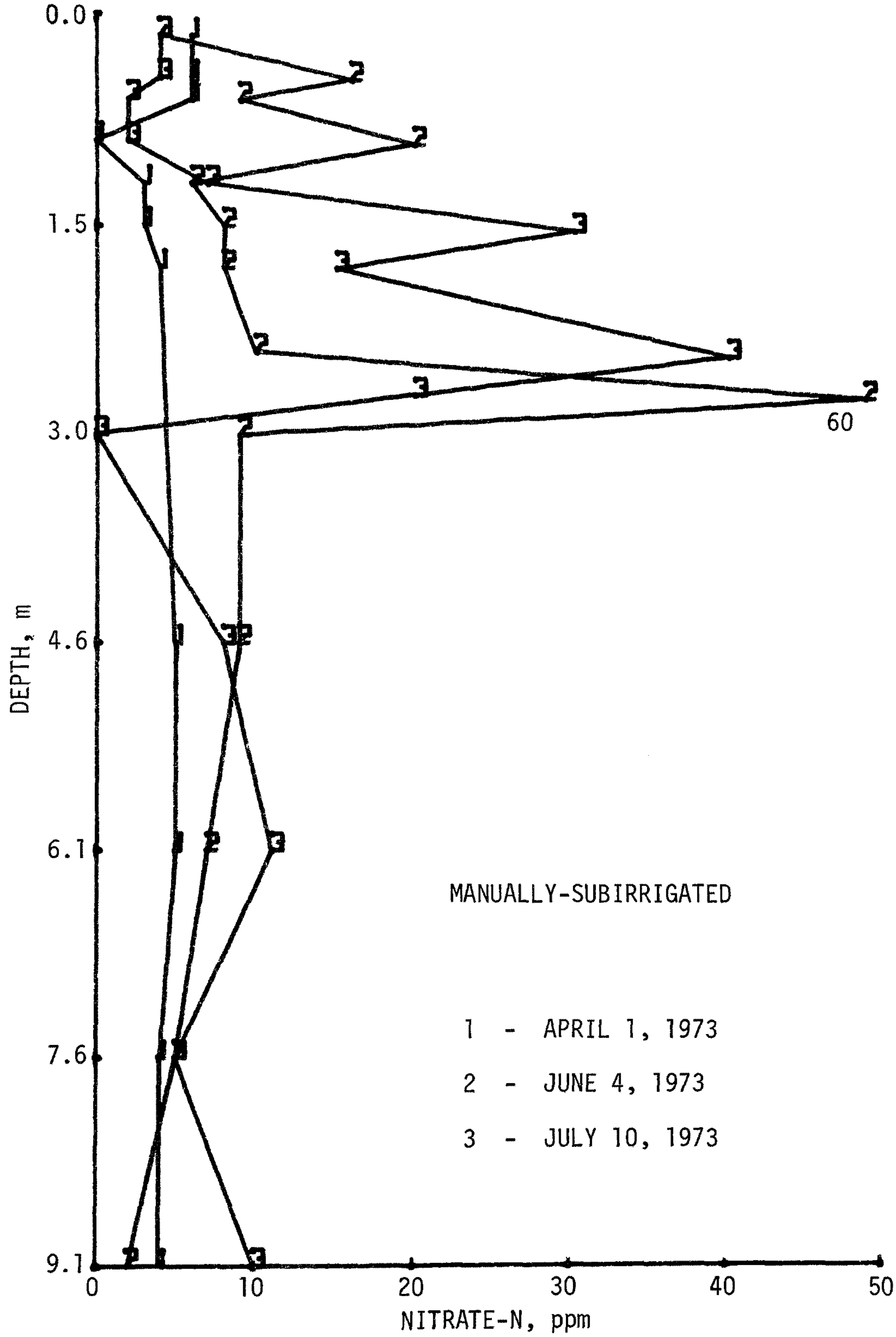


Figure 152. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1973 for a plot treated with sulfur-coated urea banded in the bed.

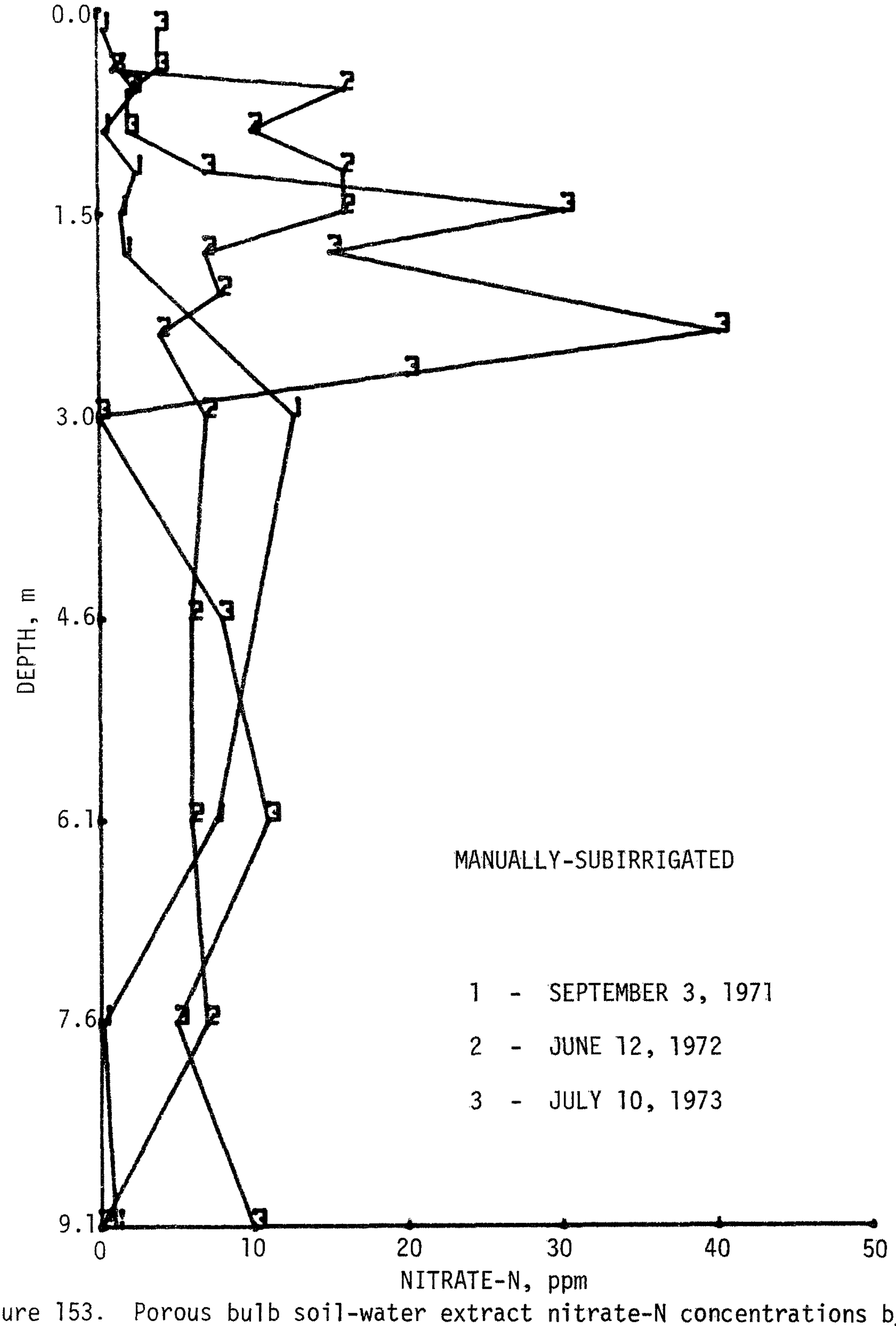


Figure 153. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971, 1972 and 1973 for a plot treated with sulfur-coated urea banded in the bed.

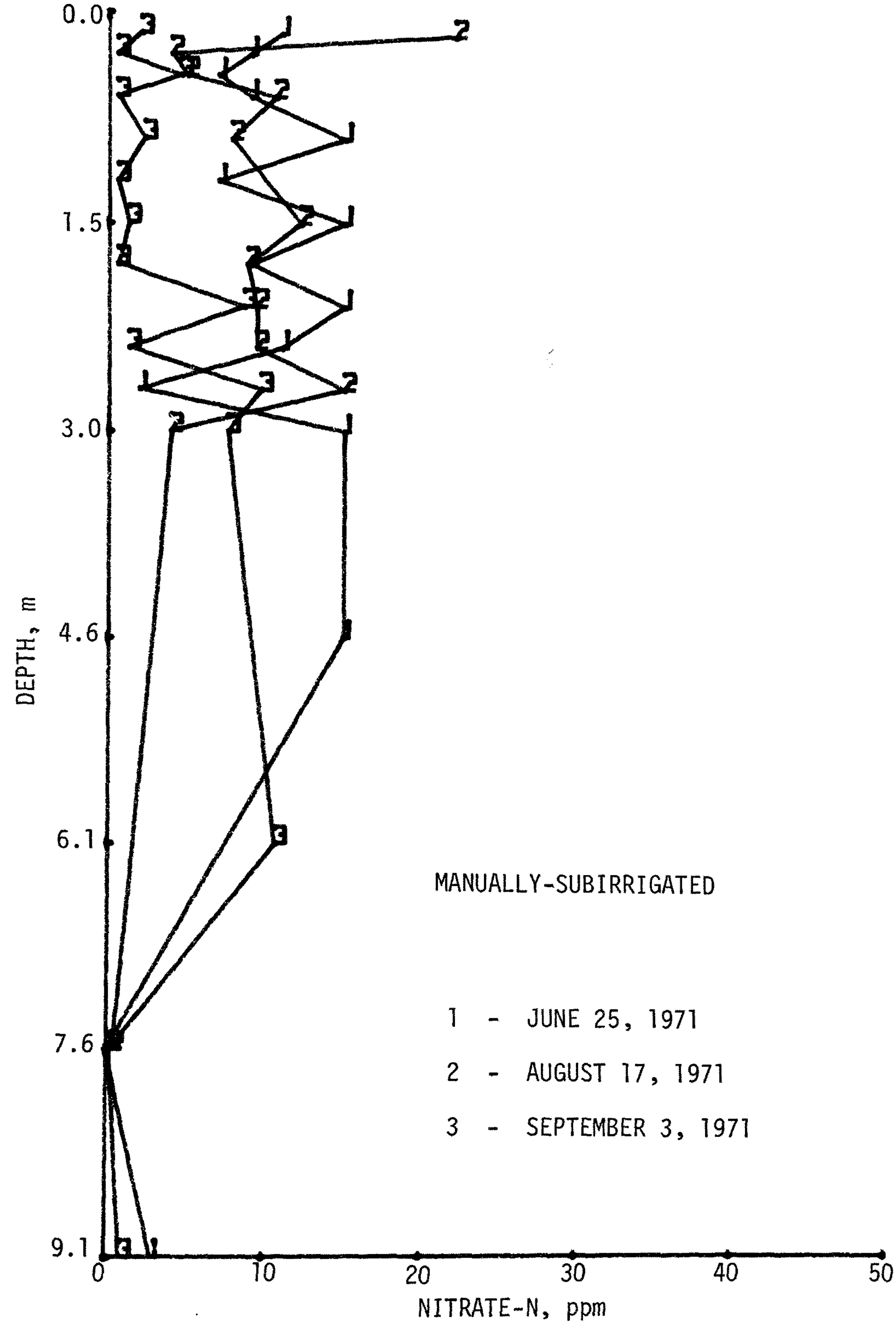


Figure 154. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971 for a plot treated with ammonia + N-Serve banded in the bed.

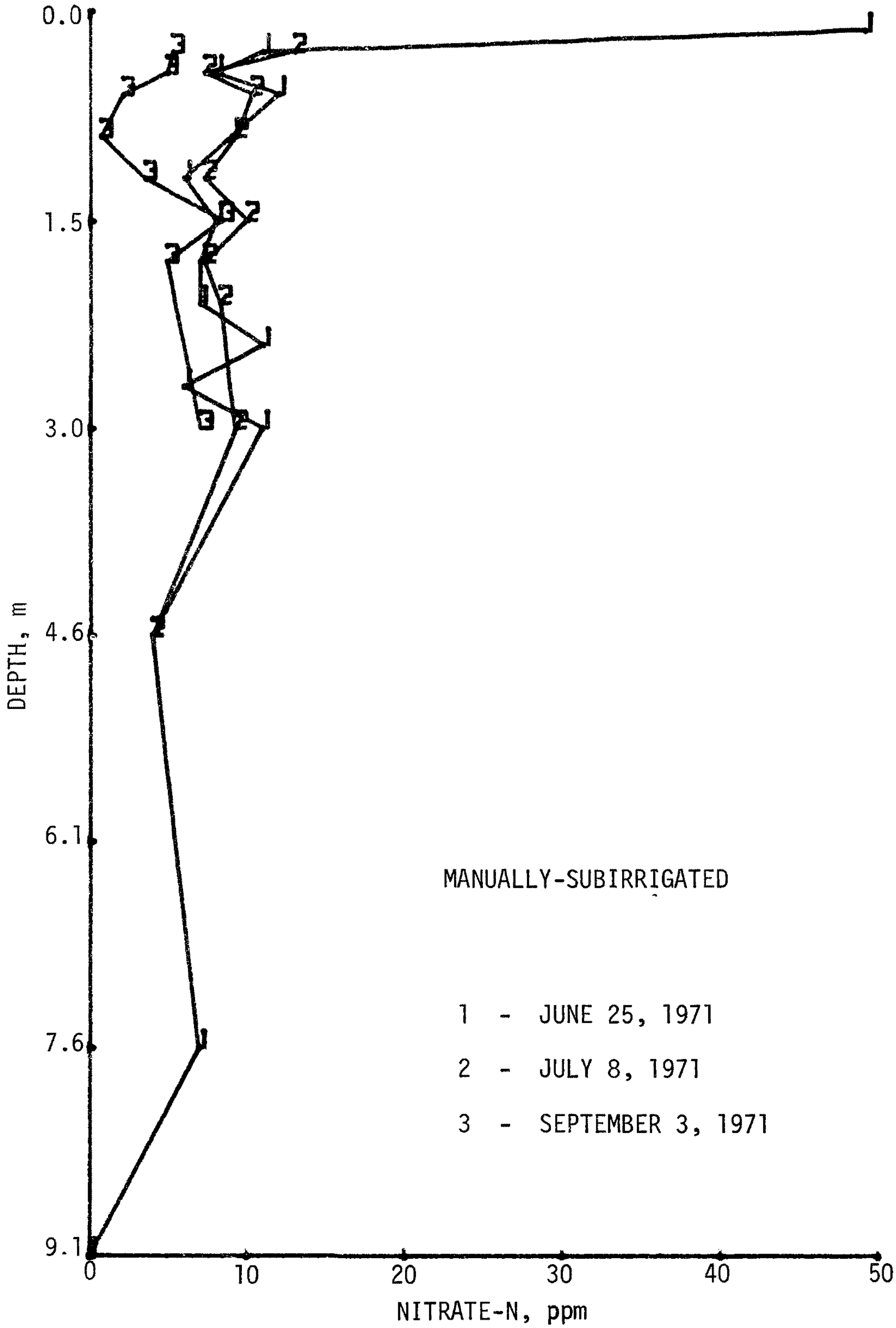


Figure 155. Porous bulb soil-water extract nitrate-N concentrations by soil depth during 1971 for a plot treated with ammonia banded in the bed.

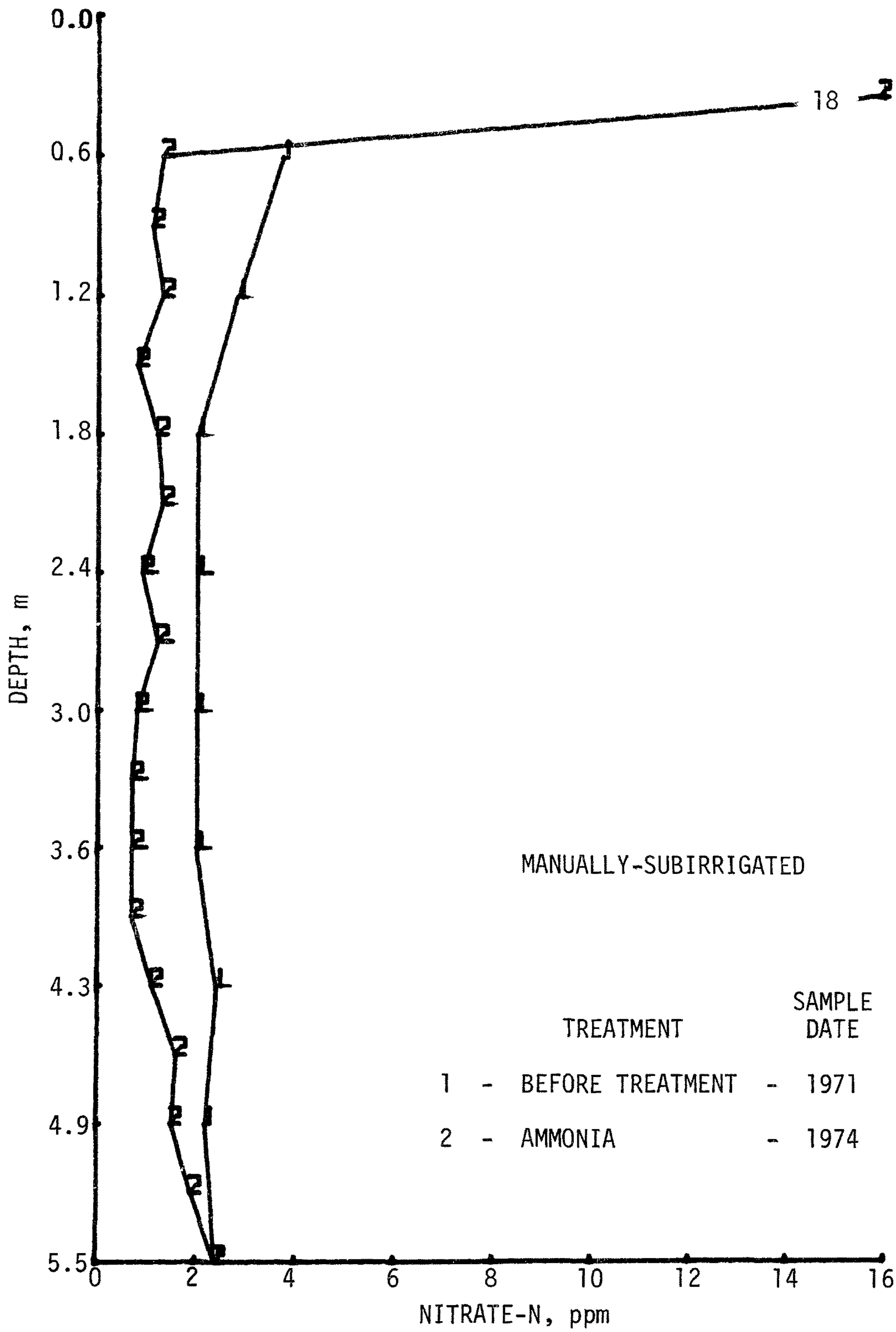


Figure 156. Soil extract (1:1) nitrate-N concentrations by soil depth before treatment (1971) and after four years of N application, 1974. (Total N - 514 kg/ha)

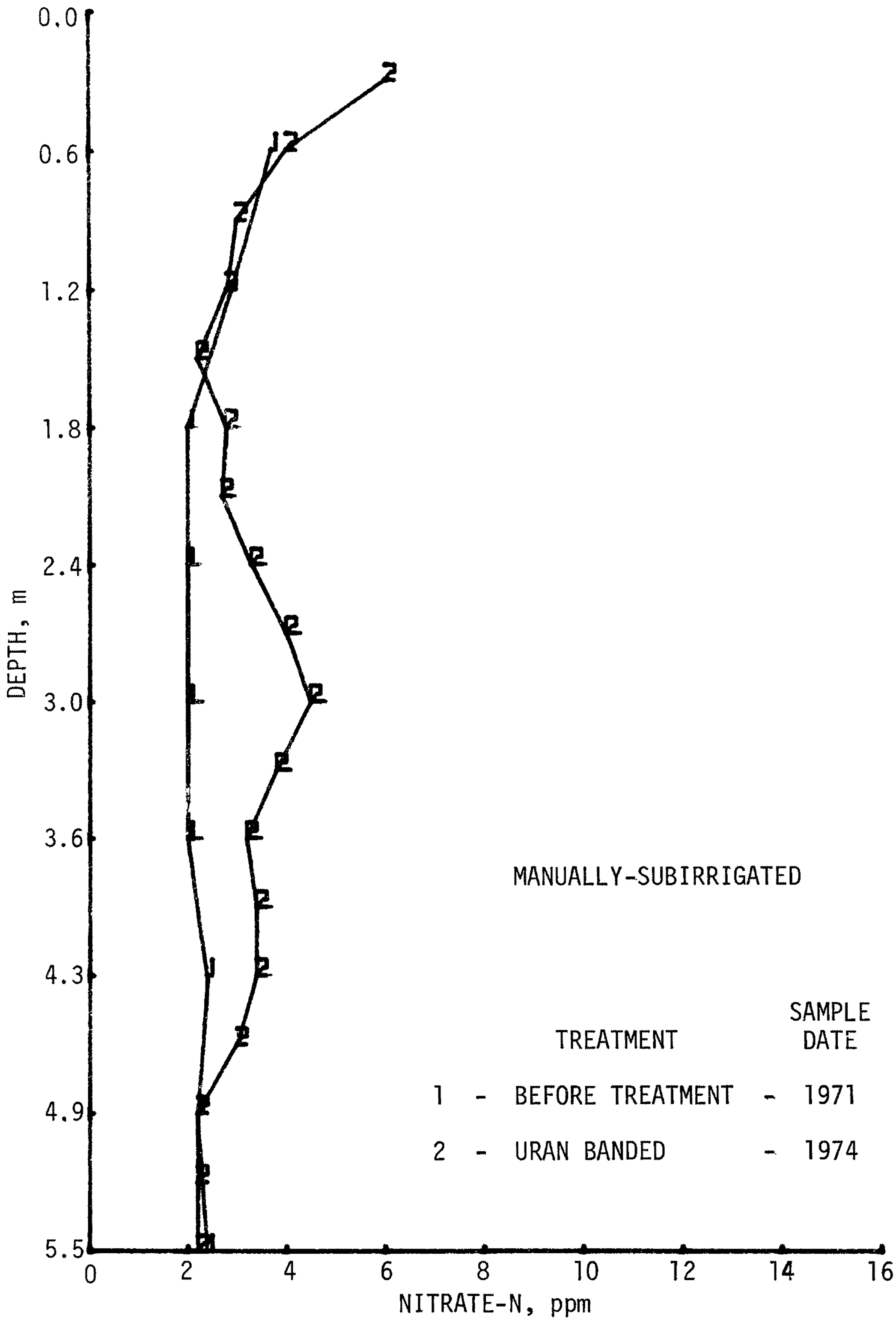


Figure 157. Soil extract (1:1) nitrate-N concentrations by soil depth before treatment (1971) and after four years of N application, 1974. (Total N - 508 kg/ha)

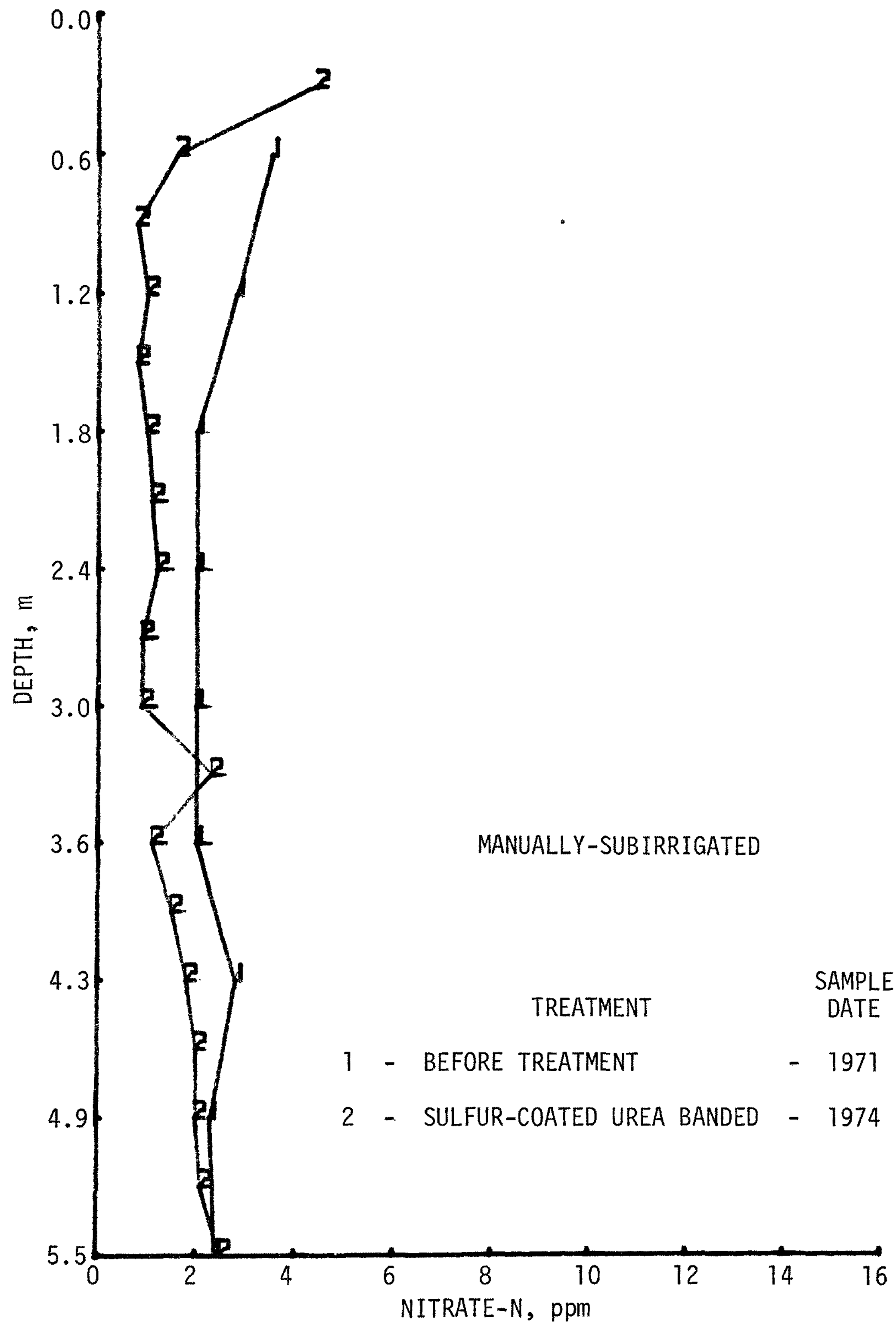


Figure 158. Soil extract (1:1) nitrate-N concentrations by soil depth before treatment (1971) and after four years of N application, 1974. (Total N - 518 kg/ha)

Isotope (^{15}N) Studies

As previously discussed, it was not possible to separate the contributions of fertilizer nitrogen and soil nitrogen to the nitrogen in the soil profile. A separate study was conducted in 1973 and 1974 to delineate these differences. Nitrogen as sodium nitrate was applied at two locations in each irrigation system at the rate of 123.6 kg/ha and 104.7 kg/ha in 1973 and 1974, respectively. Samples were obtained within the profile to points where ^{15}N could no longer be detected and analyzed as previously described. The data were analyzed both qualitatively and quantitatively. A discussion of the qualitative analyses follows.

Qualitative Studies--

Since much of the nitrogen determined was in the nitrate form and this is the ion of major concern, it is the form to be discussed in this section. The organic nitrogen determined will be discussed in the following section.

Nitrate-N from all sources (soil and fertilizer)--Total nitrate-N determinations were made as well as ^{15}N nitrate-N in order to obtain the magnitude of the contribution of fertilizer nitrogen. The data shown in Figures 159 through 164 include nitrate-N from all sources for 1973-1974. Each data point is the weighted average of five samples. Concentrations of nitrate-N in the sprinkler-irrigated plot (Figure 159) in 1973 were low in May (<10 ppm), increased to 30 to 35 ppm at 0.6 m in June and decreased again in July with the peaks occurring at 0.9 m.

In 1974, each plot to which ^{15}N was applied in 1973 was split and ^{15}N-enriched fertilizer was applied to one-half of each plot (Locations 1-1 and 2-1, Figure 160), and unenriched fertilizer was applied to the other half (Locations 1-2 and 2-2, Figure 160). The same trend relative to concentrations of nitrate-N in the sprinkler-irrigated plot was obtained in 1974 (Figure 160) as in 1973 (Figure 159) in that the highest concentrations in the surface 0 to 0.6 m occurred in June. The peak concentration of 5 ppm observed on July 27 in 1973 at 0.9 m apparently had moved to 2.1 to 2.7 m by the beginning of the growing season in 1974. Rainfall received between harvest in 1973 and planting in 1974 was 33.3 cm in 27 rainfall periods which probably accounted for this movement.

Maximum concentrations of nitrate-N from all sources observed in the furrow-irrigated plots in May of 1973 (Figure 161) were lower than those in the sprinkler-irrigated plots (Figure 159) and higher in the profile. Concentrations in samples obtained from the furrow-irrigated plots did not exceed 20 ppm which was lower than those of the sprinkler-irrigated plots. Peak concentrations in 1973 in the furrow-irrigated plots of 15 to 18 ppm were observed in June at 0.6 to 0.9 m. By July 27, the peak concentrations were at 1.2 m indicating the fertilizer moved from 0.3 m to 0.9 to 1.2 m during the growing season. Nitrate-N concentrations in samples obtained in July from the furrow-irrigated plots were generally higher than those obtained from the sprinkler-irrigated plots. At the end of the growing season, a peak concentration of 5 to 10 ppm nitrate-N was observed at 1.2 to 1.5 m compared to a similar but lower peak in the sprinkler-irrigated plots at 0.9 m.

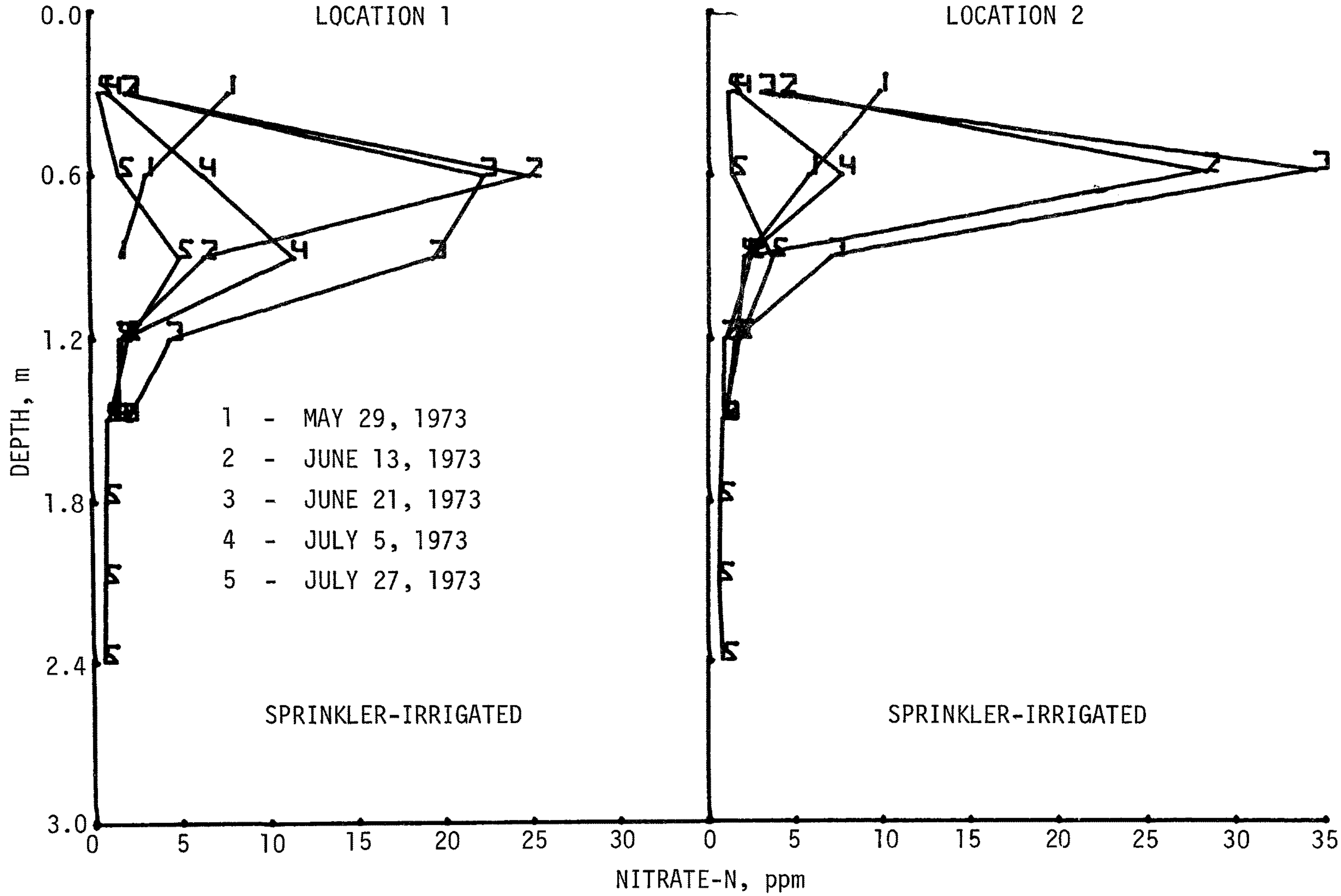


Figure 159. Concentrations of nitrate-N from all sources by depth in 1973 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

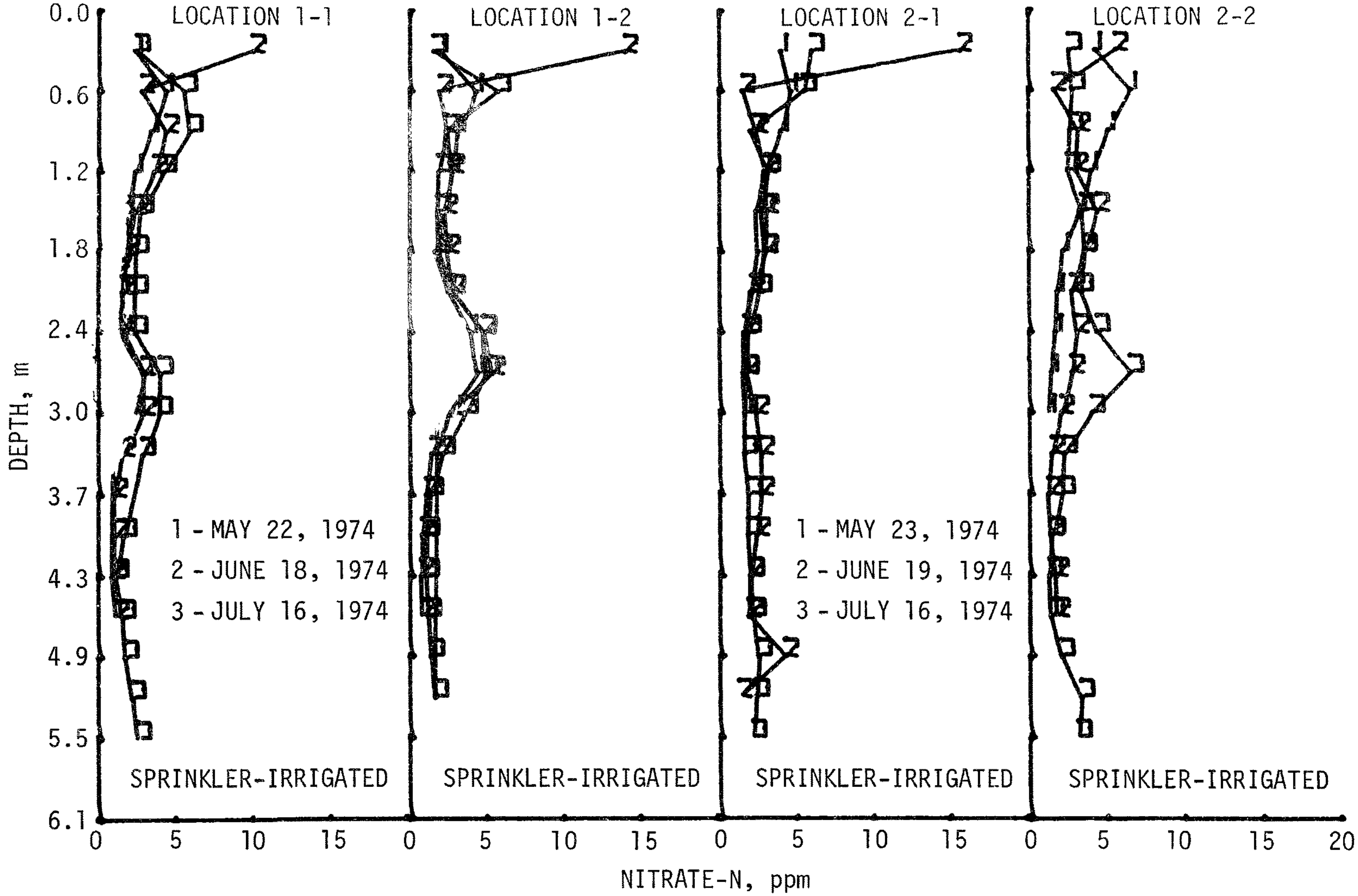


Figure 160. Concentrations of nitrate-N from all sources by depth in 1974 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

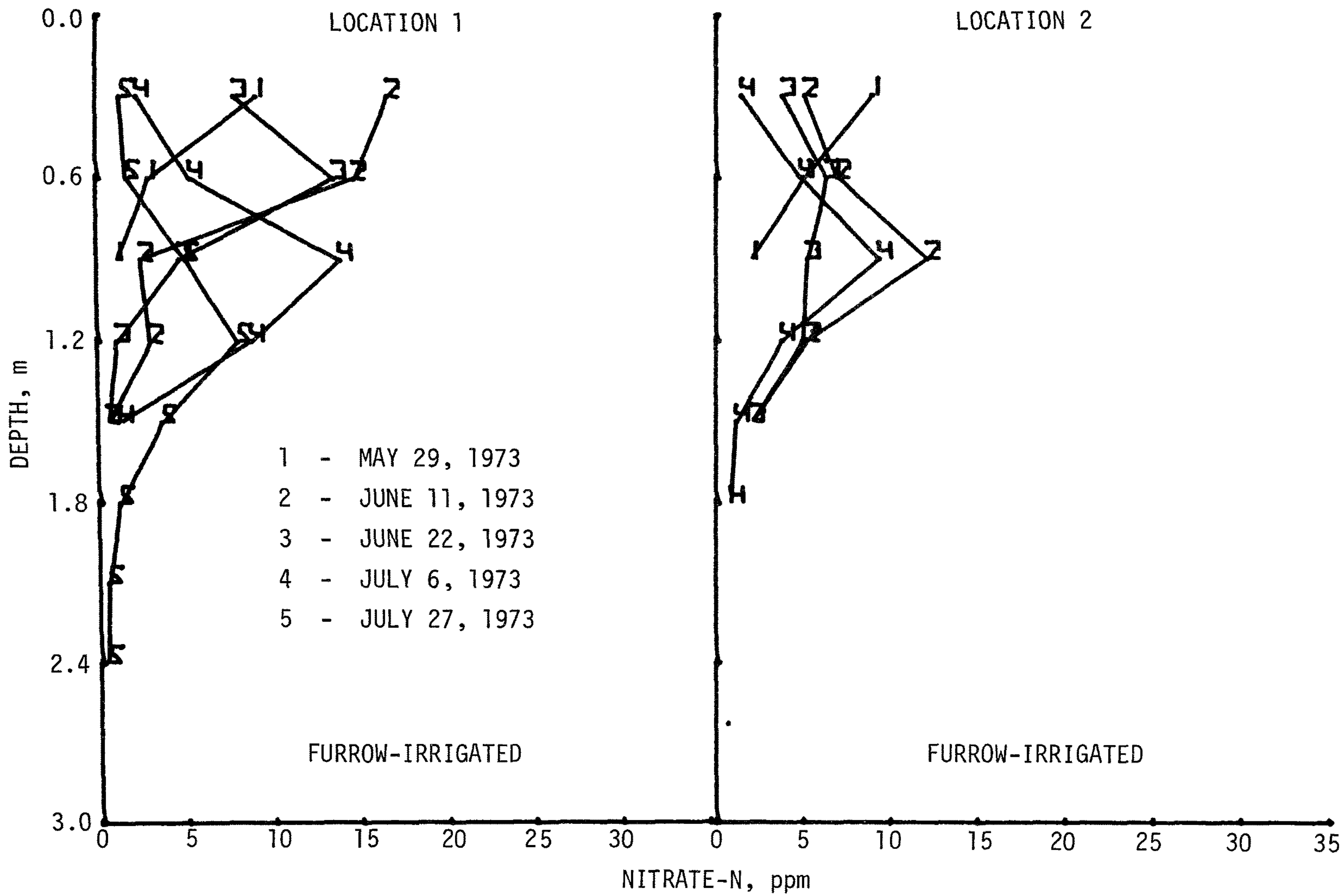


Figure 161. Concentrations of nitrate-N from all sources by depth in 1973 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

In 1974, concentrations of nitrate-N in the surface 2.4 m were generally higher in the furrow-irrigated plots (Figure 162) than in the sprinkler-irrigated plots (Figure 160). Peak concentrations of nitrate-N at the end of the growing season at 1.2 to 1.5 m in 1973 were observed at 1.8 to 2.4 m at the beginning of the 1974 growing season in the furrow-irrigated plots, indicating that the peaks did not move as far in the furrow-irrigated plots as in the sprinkler-irrigated plots (Figure 160). High concentrations of nitrate-N were also noted in the surface 0.6 m in both the sprinkler- (Figure 160) and furrow-irrigated plots (Figure 162).

As with the sprinkler- and furrow-irrigated plots, the nitrate-N concentrations from all sources in the subirrigated plots in 1973 (Figure 163) were low in May, highest in June and decreased in July. Highest concentrations were at 0.3 m in the subirrigated plots compared to 0.3 to 0.9 m in the sprinkler- (Figure 159) and furrow-irrigated (Figure 161) plots. At the end of the growing season (July 30), concentrations in the subirrigated plots (Figure 163) were less than 1 ppm which was much lower than those of the sprinkler- (Figure 159) and furrow-irrigated (Figure 161) plots.

Peak concentrations of nitrate-N from all sources in the subirrigated plots in 1974 (Figure 164) was high at 0.3 m (15 to 29 ppm) and decreased sharply with depth so that concentrations below 0.6 m were generally less than 2 ppm, which was less than those of the sprinkler- and furrow-irrigated plots.

Nitrate-N from fertilizer--As discussed initially, the primary concern of this study was to determine the fate of fertilizer nitrogen. As with nitrogen from all sources, relatively high concentrations of fertilizer nitrate-N were found in the sprinkler-irrigated plots in June in 1973 (Figure 165) following the sidedress application of fertilizer on June 4. Concentrations decreased as the season progressed so that low concentrations of fertilizer nitrate-N existed in the soil at the end of the growing season. No fertilizer nitrate-N was located below 0.9 m at the end of the growing season.

At the beginning of the 1974 season (Figure 166), concentrations of fertilizer nitrate-N were noted at 2.4 to 2.7 m indicating some movement during the period when a crop was not growing. The concentrations are too low (<5 ppm) to be of concern. However, if an excess of nitrate-N from fertilizer would have been available, the data indicate that it would have moved from 0.9 m to 2.7 to 3.0 m from the 33.3 cm of rainfall received between the 1973 and 1974 growing seasons.

It is notable that insignificant amounts of fertilizer nitrate-N were found in the root zone of the subplots (Locations 1-2 and 2-2, Figure 166) which were not fertilized with ^{15}N-enriched fertilizer in 1974. Further, high concentrations of fertilizer nitrate-N were not observed in the plots treated with ^{15}N-enriched fertilizer in 1974 indicating that if recommended rates of fertilizer are used, concentrations within the profile can be kept at levels which will not be of concern.

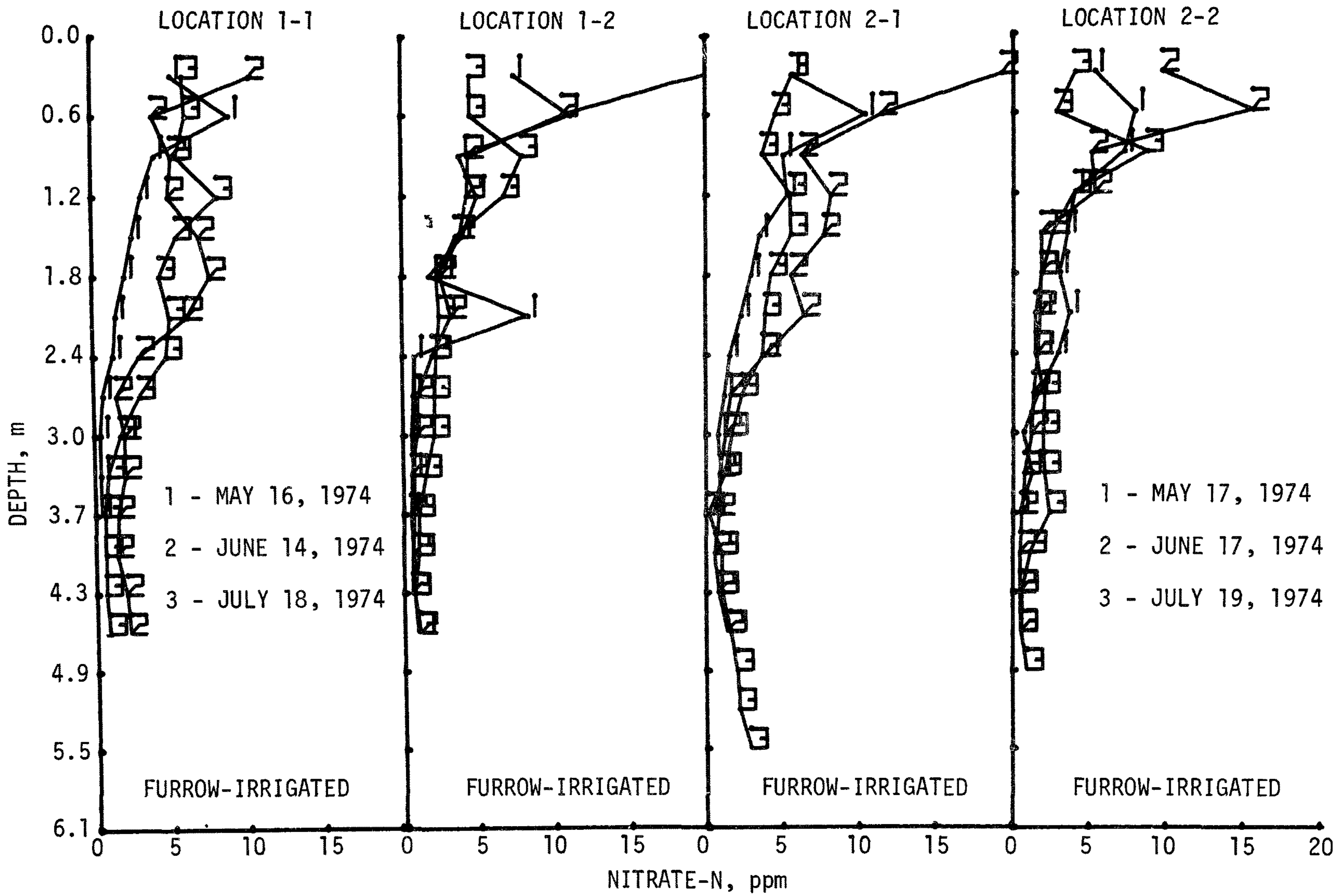


Figure 162. Concentrations of nitrate-N from all sources by depth in 1974 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

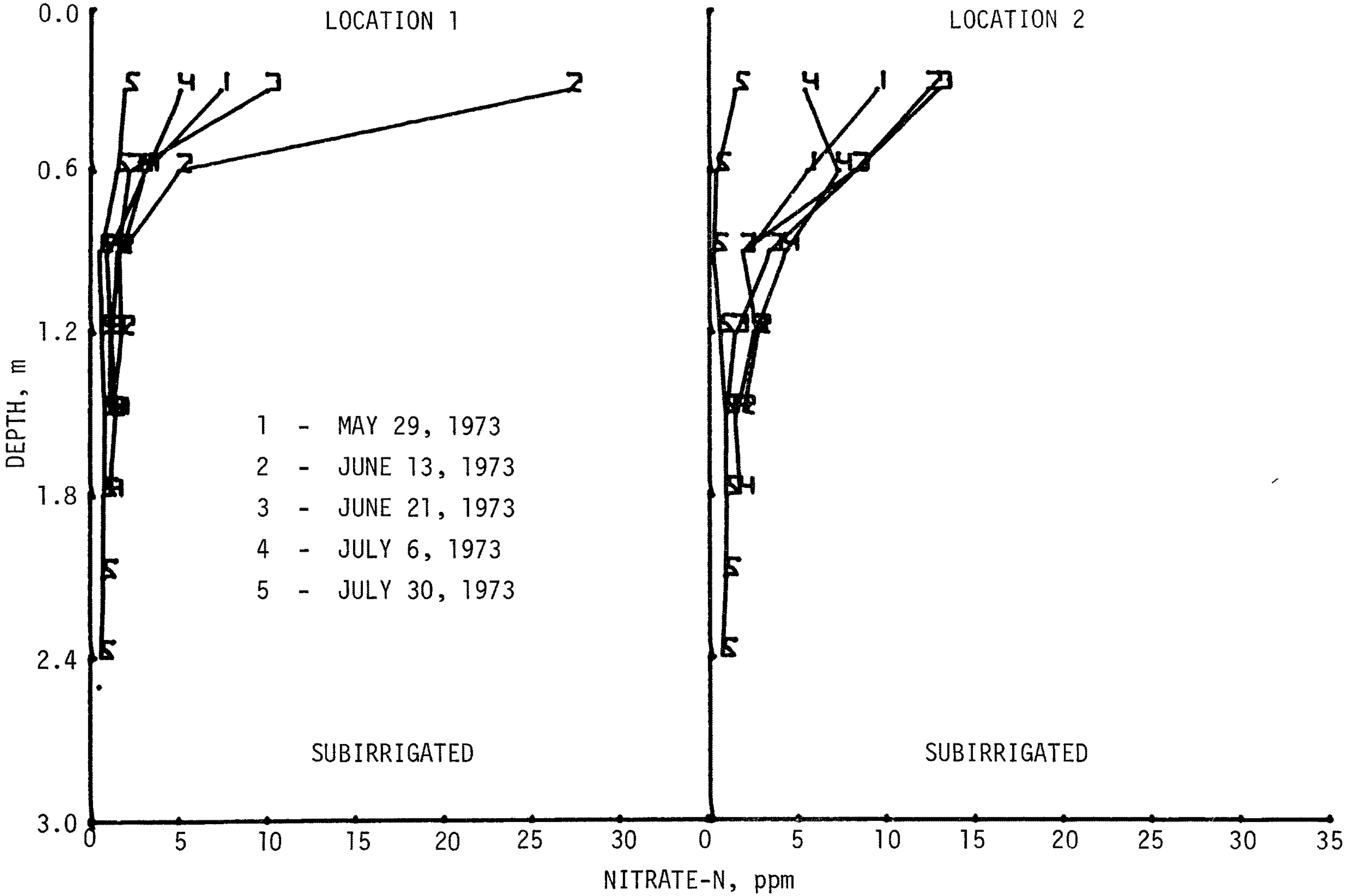


Figure 163. Concentrations of nitrate-N from all sources by depth in 1973 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

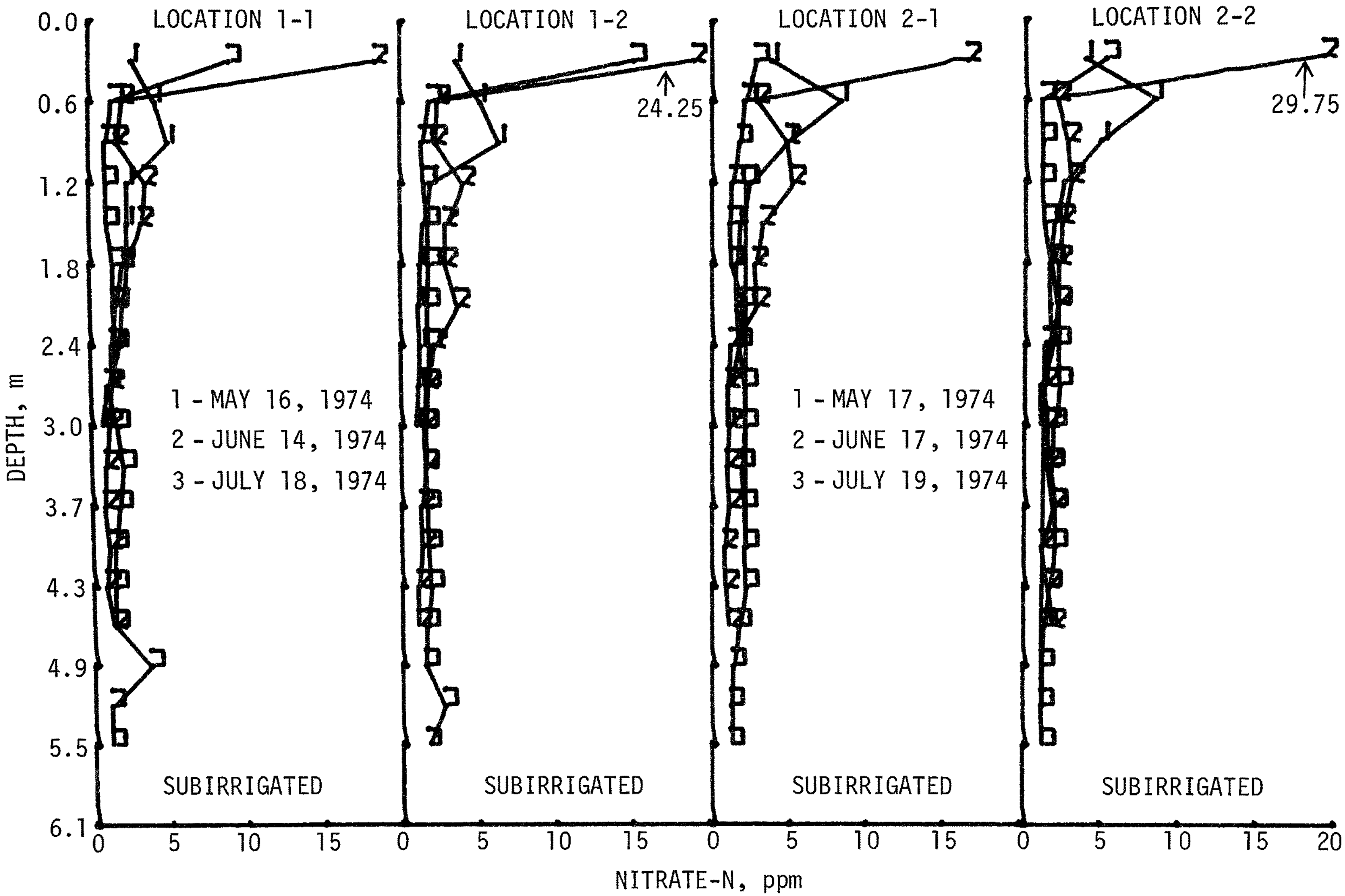


Figure 164. Concentrations of nitrate-N from all sources by depth in 1974 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

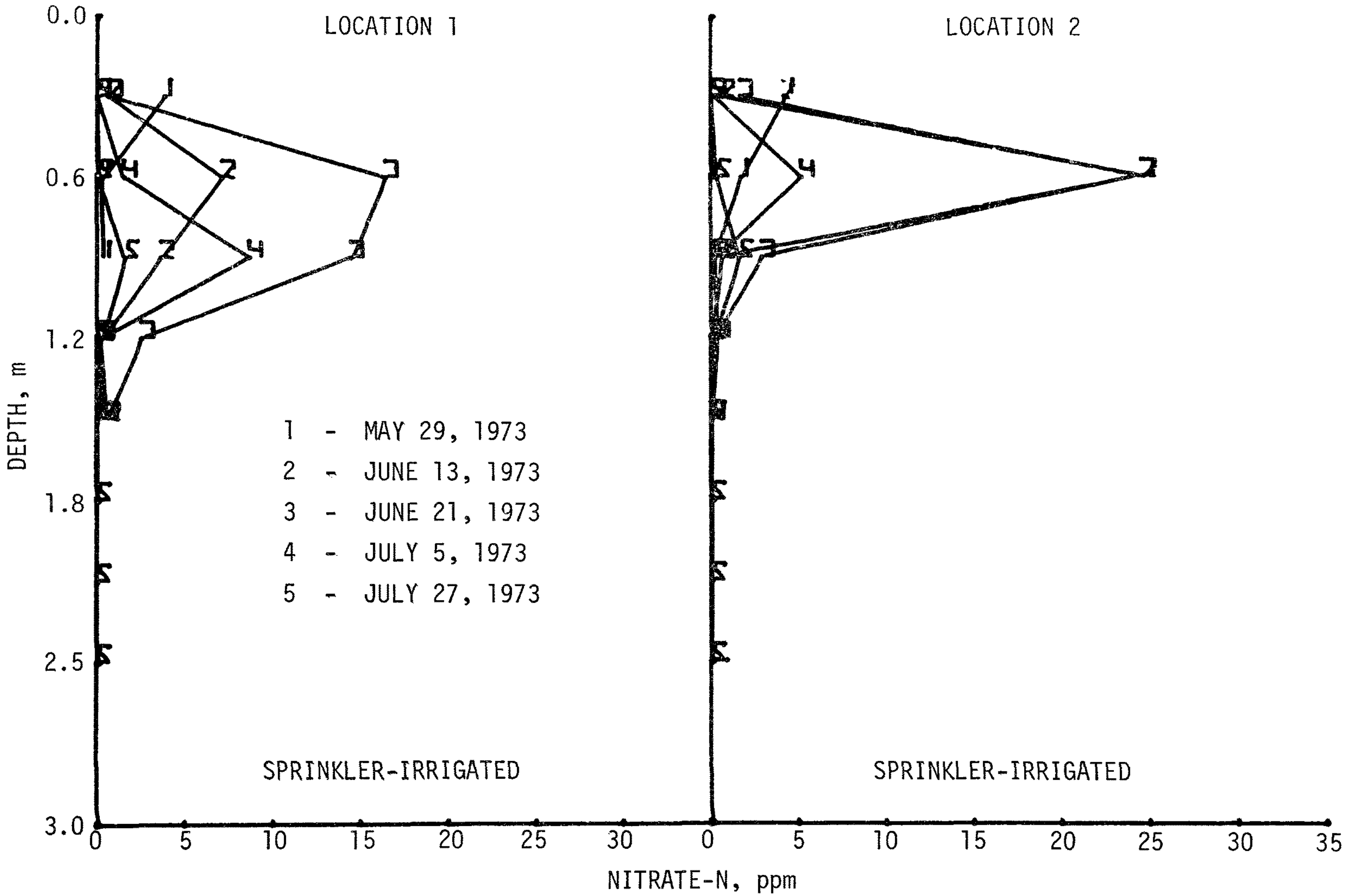


Figure 165. Concentrations of fertilizer nitrate-N by depth in 1973 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

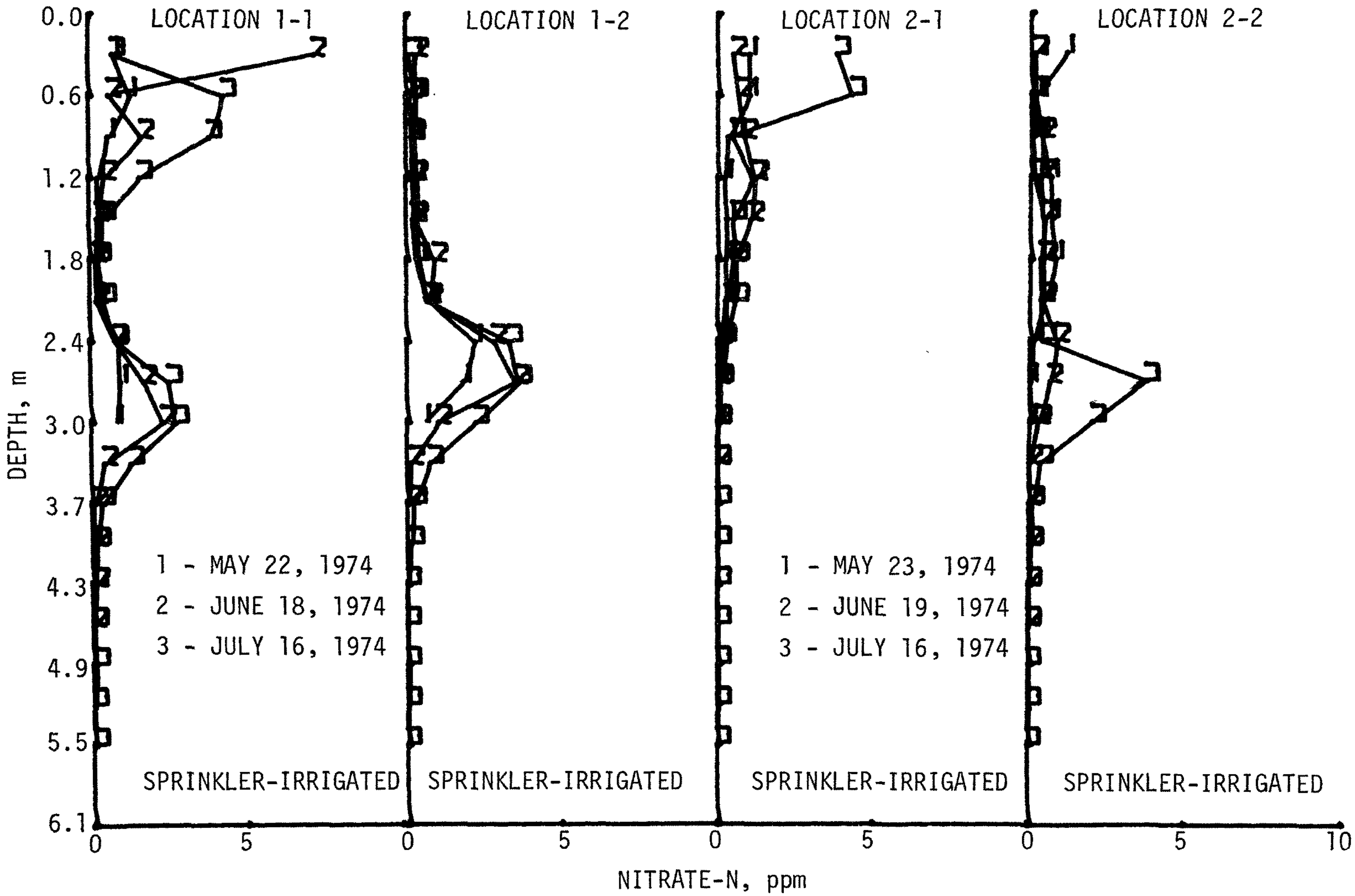


Figure 166. Concentrations of fertilizer nitrate-N by depth in 1974 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

As with the nitrate-N from all sources, the fertilizer nitrate-N concentrations in the furrow-irrigated plots in 1973 (Figure 167) were not as high as in the sprinkler-irrigated plots (Figure 165). Concentrations were 10 ppm or less in the furrow plots compared to 30 ppm in the sprinkler plots. Also, concentrations of fertilizer nitrate-N were located deeper within the profile (1.2 to 1.5 m) of the furrow-irrigated plots than the sprinkler-irrigated plots (0.9 m) at the end of the growing season.

In 1974, a major difference between the furrow-irrigated plots (Figure 168) and the sprinkler-irrigated plots (Figure 166) was the large amount of fertilizer nitrate-N detected in the 1.2 to 2.4 m zone. Differences in the concentrations of nitrate-N from all sources in all furrow plots were not great (Figure 162) but significant differences existed in the amount of fertilizer nitrate-N in plots fertilized with ^{15}N-enriched fertilizer in 1974 (Locations 1-1 and 2-1) and those fertilized with unenriched fertilizer (Locations 1-2 and 2-2). These data indicate that nitrogen applied as fertilizer in 1974 leached into the 1.2- to 2.4-m zone.

Concentrations of fertilizer nitrate-N in the subirrigated plot (Figure 169) followed a pattern similar to that of nitrate-N from all sources in that the concentrations below 0.6 m were significantly lower in the subirrigated plots (Figure 169) than in the sprinkler- (Figure 165) and furrow-irrigated (Figure 167) plots.

In 1974, significant amounts of fertilizer nitrate-N applied in 1973 were not detected in subirrigated plots (Figure 170) which were not fertilized with ^{15}N-enriched fertilizer in 1974. As will be discussed in detail later, this is ideal from the standpoint of irrigation return flow. With the exception of the concentrations at 0.3 m, the values for fertilizer nitrate-N of the subirrigated plots fertilized with ^{15}N-enriched nitrogen in 1974 (Locations 1-1 and 2-1) were significantly lower in the subirrigated plots (<1 ppm, Figure 170) than in the sprinkler-irrigated (Figure 166) or the furrow-irrigated plots (Figure 168) and were too low to be of concern.

Percent nitrate-N as fertilizer nitrogen--Since the nitrate-N levels of the ^{15}N-fertilized plots were relatively low, it was difficult to get a feel for the potential pollution problem by nitrate-N from fertilizer. It was therefore decided to view the percent of nitrate-N that was fertilizer nitrate-N since percentages would better emphasize the contributions of fertilizer than the low concentrations.

In the sprinkler-irrigated plot in 1973 (Figure 171), the maximum percentages of fertilizer nitrate-N (80% to 90%) were obtained at 0.6 m in June with lower values above and below this depth. At the end of the season, the maximum value (25% to 40%) was obtained at 0.9 m. The data thus show that a high percentage of the nitrate-N in the root zone was from the fertilizer and that insignificant amounts had moved below the root zone during the growing season.

At the beginning of the 1974 season, over 75% of the nitrate-N at 2.4 to 3.0 m was from fertilizer in the sprinkler-irrigated plots (Figure 172). Since actual concentrations were low, the amounts present were not

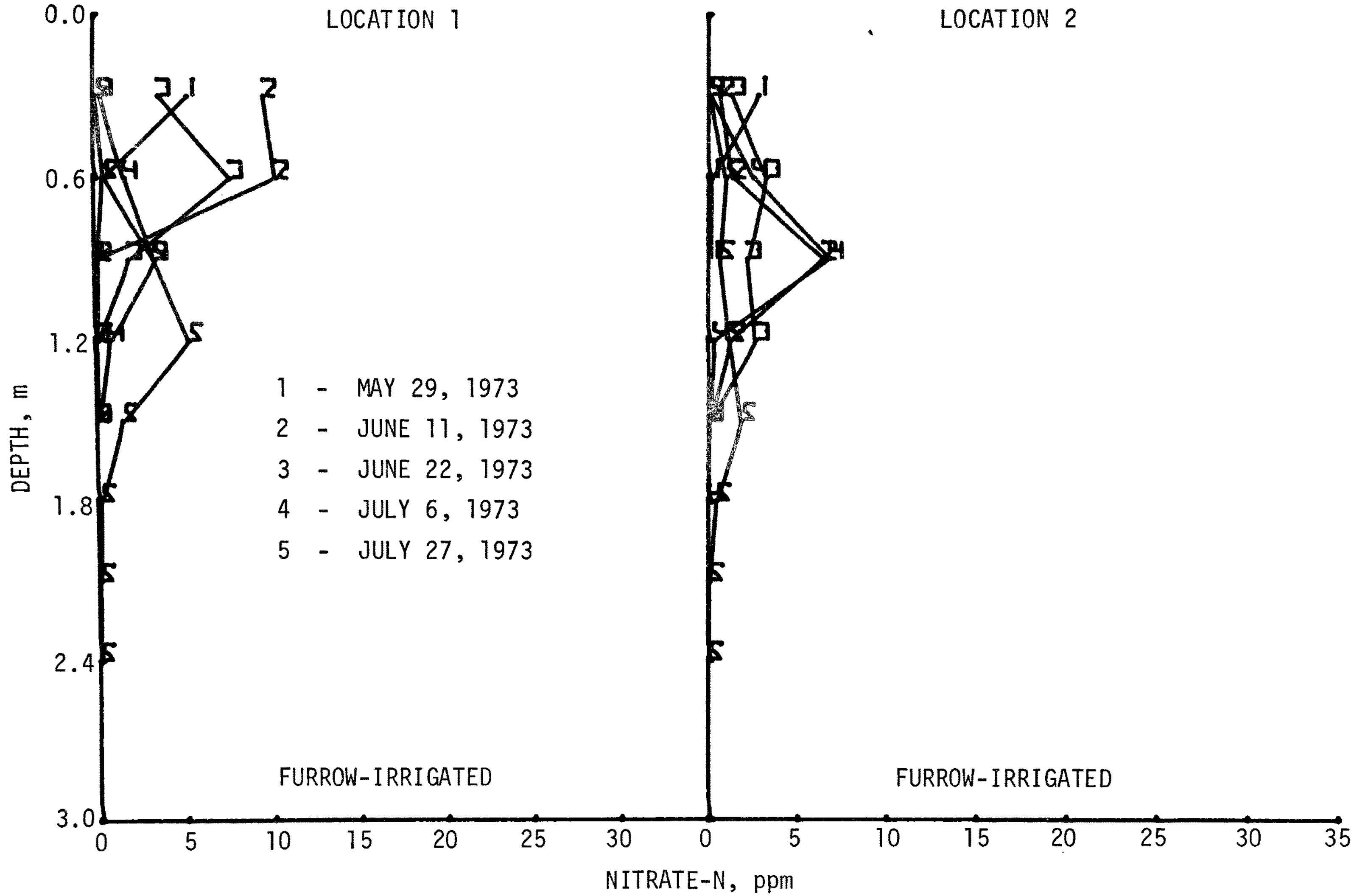


Figure 167. Concentrations of fertilizer nitrate-N by depth in 1973 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

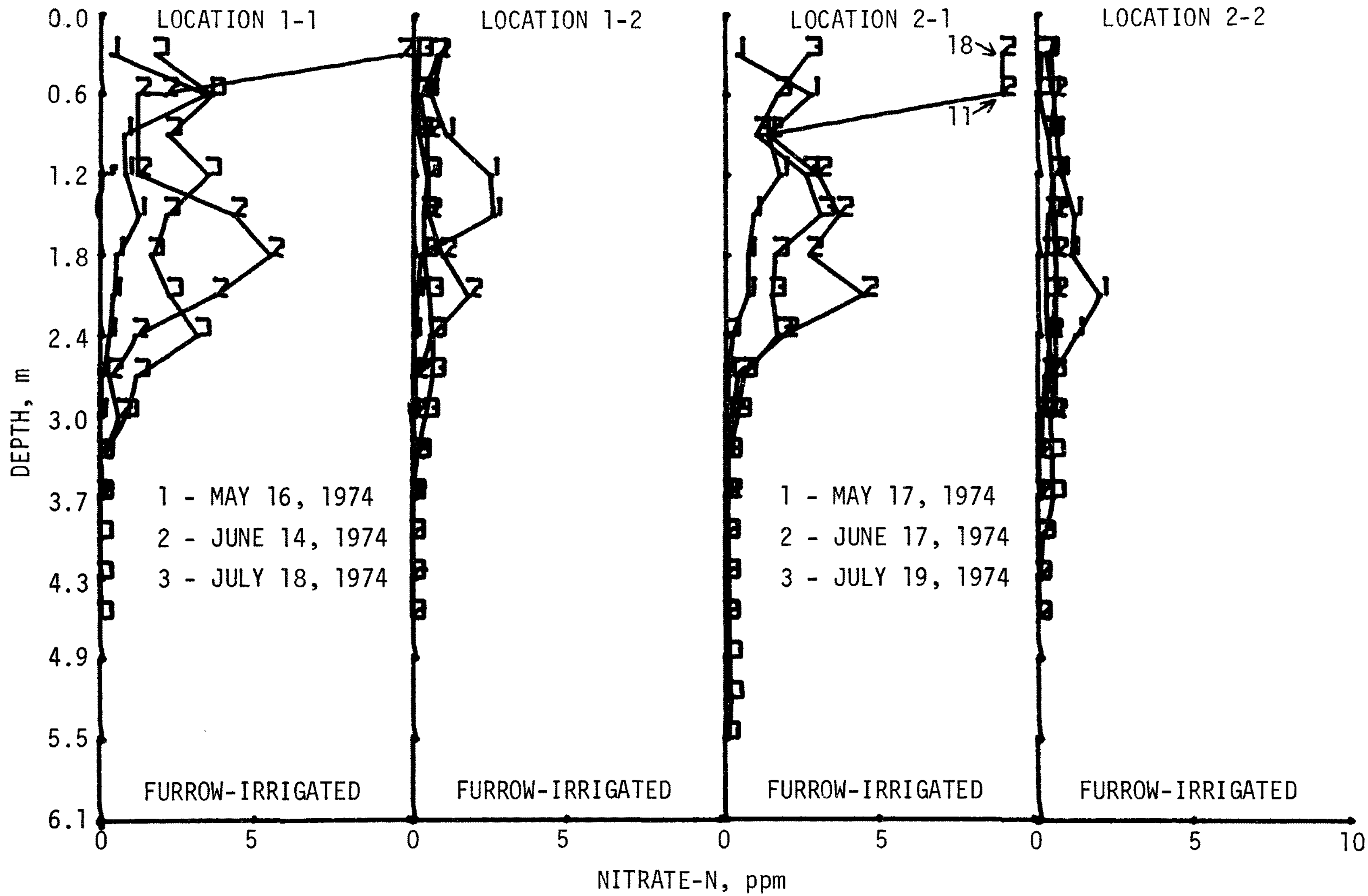


Figure 168. Concentrations of fertilizer nitrate-N by depth in 1974 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

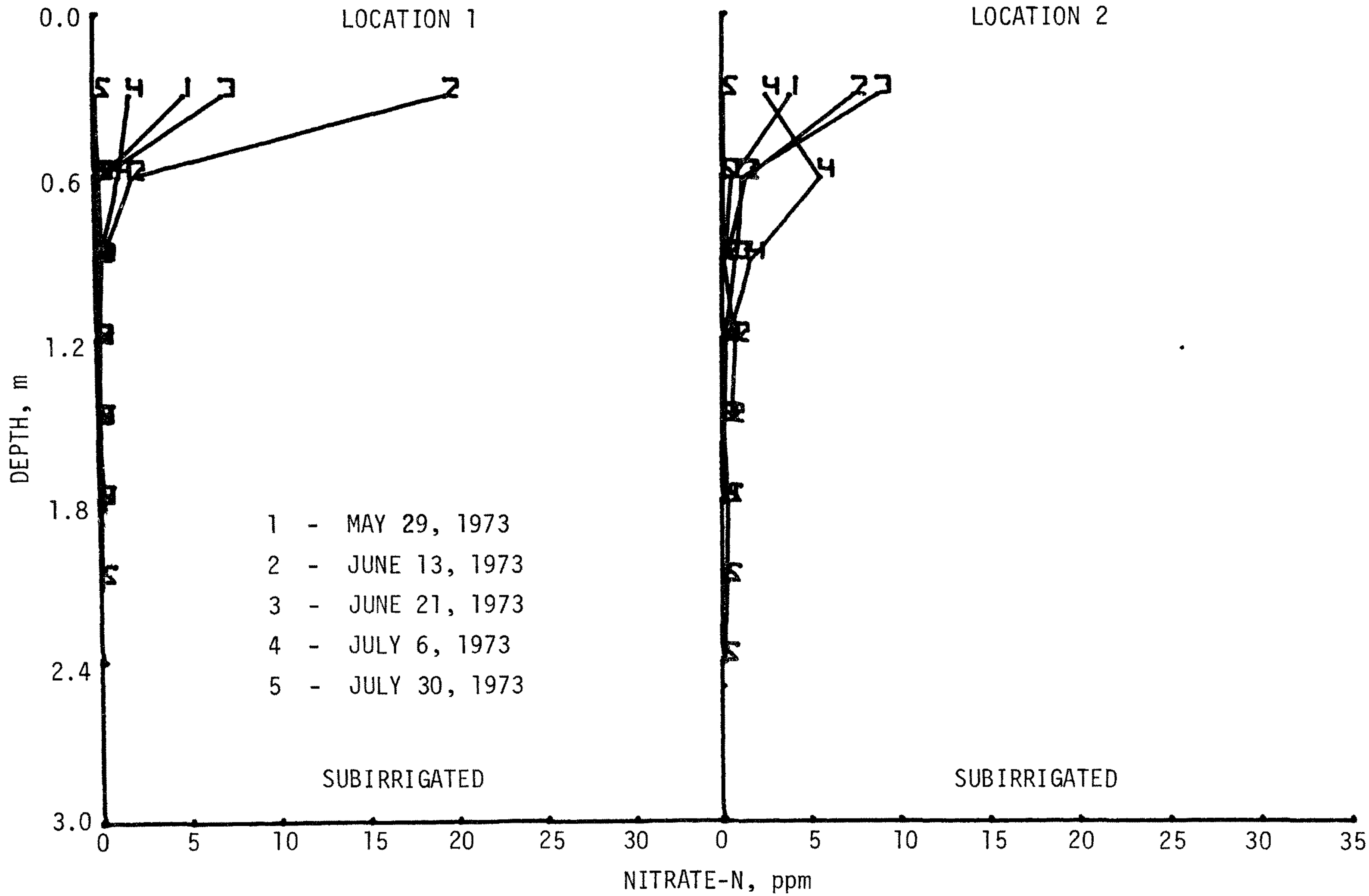


Figure 169. Concentrations of fertilizer nitrate-N by depth in 1973 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

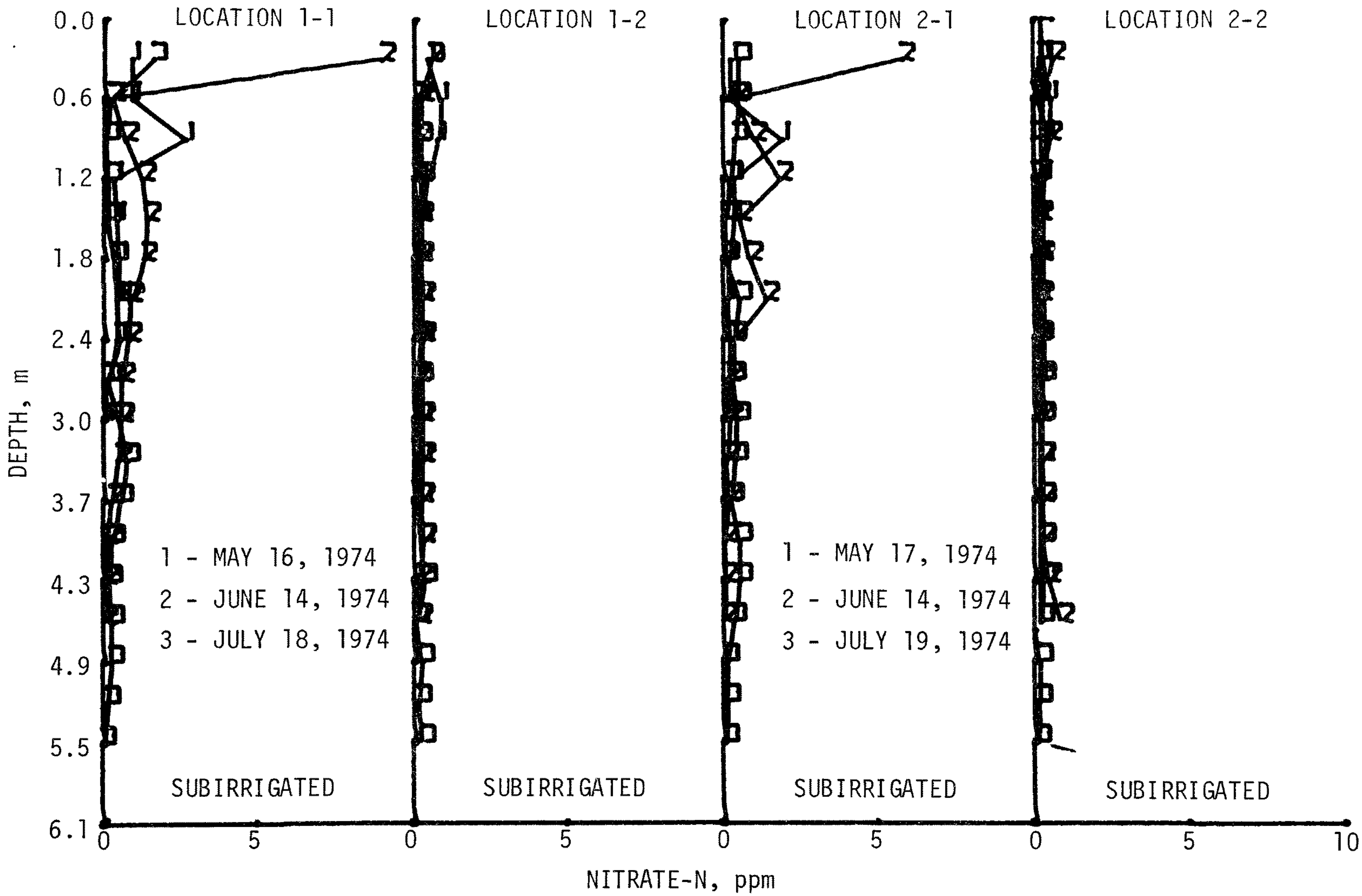


Figure 170. Concentrations of fertilizer nitrate-N by depth in 1974 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

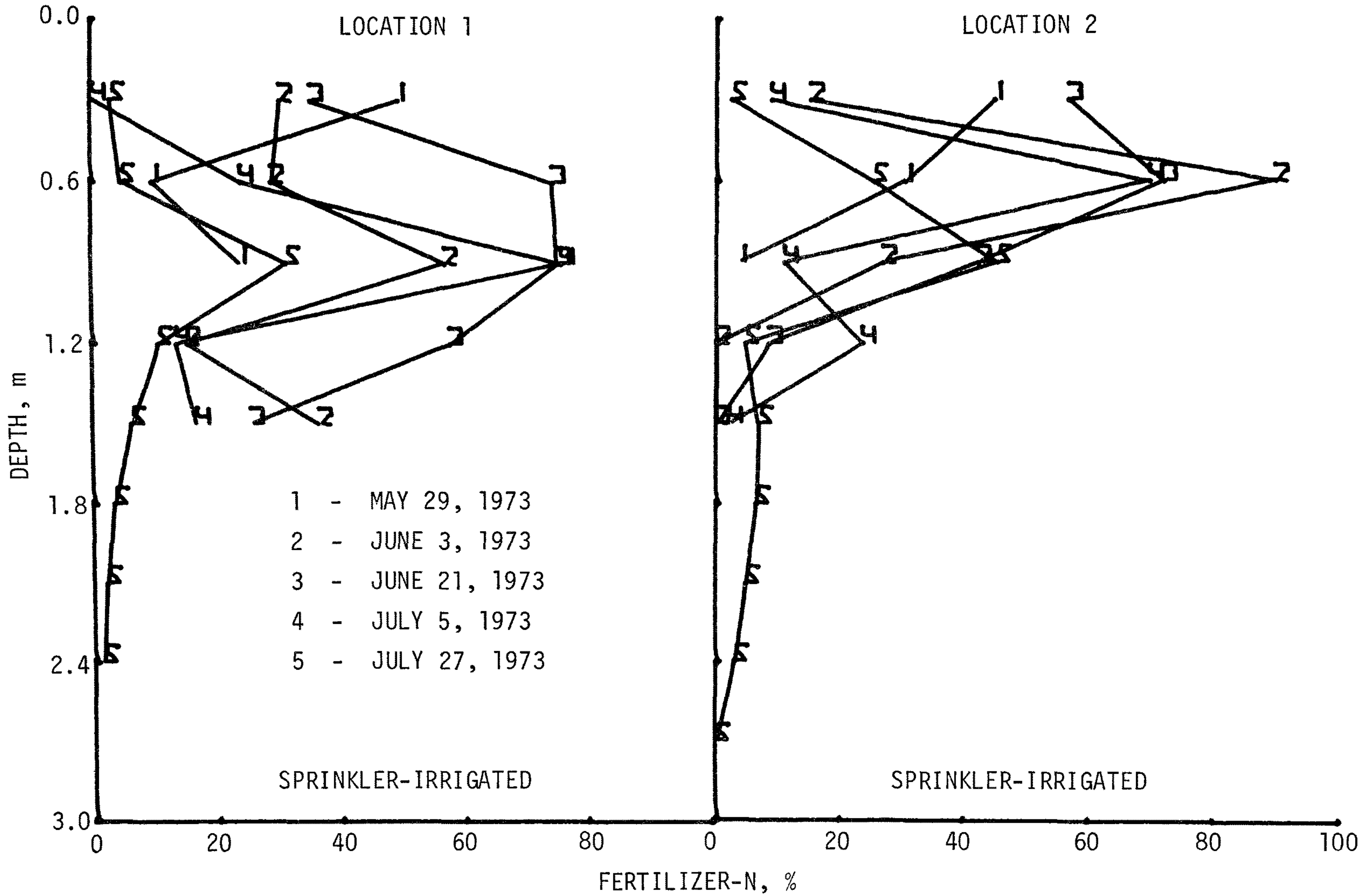


Figure 171. Percent nitrate-N from fertilizer by depth in 1973 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

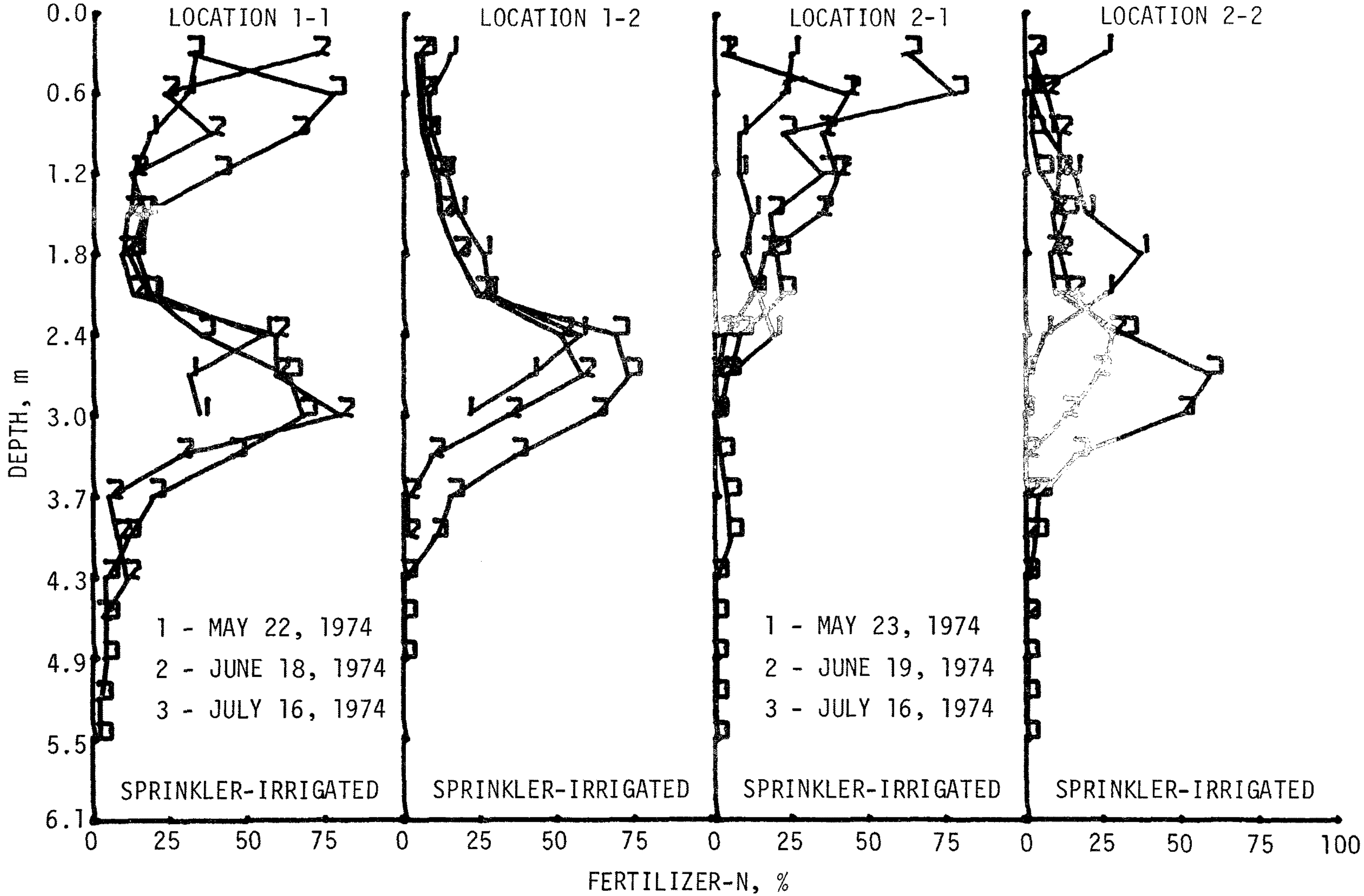


Figure 172. Percent nitrate-N from fertilizer by depth in 1974 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

significant (Figure 166). However, if an excess had been applied, a significant amount of fertilizer nitrate-N would have been located at this depth.

In the furrow-irrigated plot in 1973 (Figure 173), up to 60% of the nitrogen present in the nitrate form in the root zone was from fertilizer. This was not as high as in the sprinkler-irrigated plot (Figure 161) but it was spread over a wider band. At the end of the season (July 27, 1973), 40% to 50% of the nitrate-N present at 0.9 to 1.2 m was fertilizer nitrogen which was much higher than in the sprinkler-irrigated plot. Again, the concentrations were small (Figure 167).

The same trend carried into the 1974 season in the furrow-irrigated plot (Figure 174). As much as 50% of the nitrate-N at 1.5 to 2.1 m was from fertilizer at the beginning of the season (May 16). As the season progressed, the percentages decreased or remained approximately the same and moved to depths of 2.4 to 4.3 m by July 19, 1974, indicating movement of nitrate-N from fertilizer applied in 1973 in the furrow-irrigated plots which did not occur in the sprinkler-irrigated plots (Figure 172).

Fertilizer nitrate-N percentages as high as 60 were noted in the subirrigated plots in the surface 0.6 m (Figure 175). In general, percentages below this depth were 20 or less which was much lower than those found in the sprinkler- (Figure 171) or furrow-irrigated plots (Figure 173) at similar depths. Again, the concentrations in the subirrigated plots were low (Figure 170).

In 1974, the percentages at Location 1-1 in the subirrigated plot (Figure 176) approached 50 at almost all depths in the surface 3.3 m. However, the concentrations at these depths with the exception of the 0.3-m depth were generally less than 2 ppm (Figure 170) so the values are of no major concern. It does point out, however, the possibility of major leaching of fertilizer nitrate-N during the growing season if excess amounts are present.

<u>Summary</u>--Differences in concentrations of nitrate-N from all sources, fertilizer nitrate-N and percent nitrate-N from fertilizer differed among the sprinkler, furrow, and subirrigation systems during the two years of the study. Highest concentrations from all sources in 1973 were obtained in the sprinkler plots followed by the furrow and subirrigation plots. With the exception of the surface 0.6 m, little nitrate-N was found in the subirrigation system while significant concentrations were found down to 1.2 m in the sprinkler and furrow systems.

Leaching of nitrate-N from all sources from 0.9 m to 2.7 m apparently occurred in the sprinkler system between the 1973 and 1974 growing seasons. Some leaching was noted in the furrow systems with none being noted in the subirrigation systems. Significantly higher nitrate-N concentrations were noted in the furrow systems between 1.2 and 2.4 m than in the sprinkler and subirrigation systems showing more leaching below the root zone during the growing season.

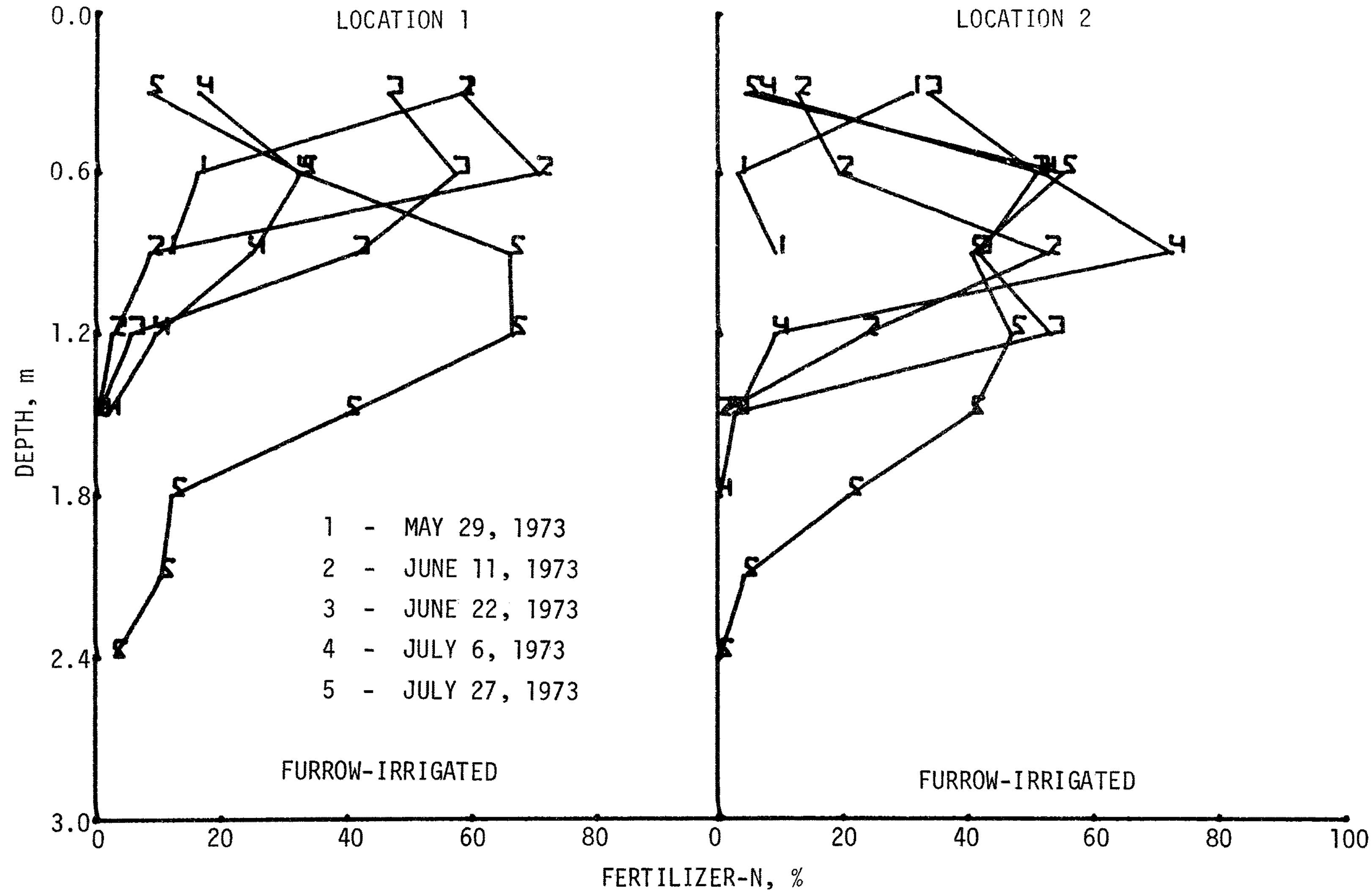


Figure 173. Percent nitrate-N from fertilizer by depth in 1973 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

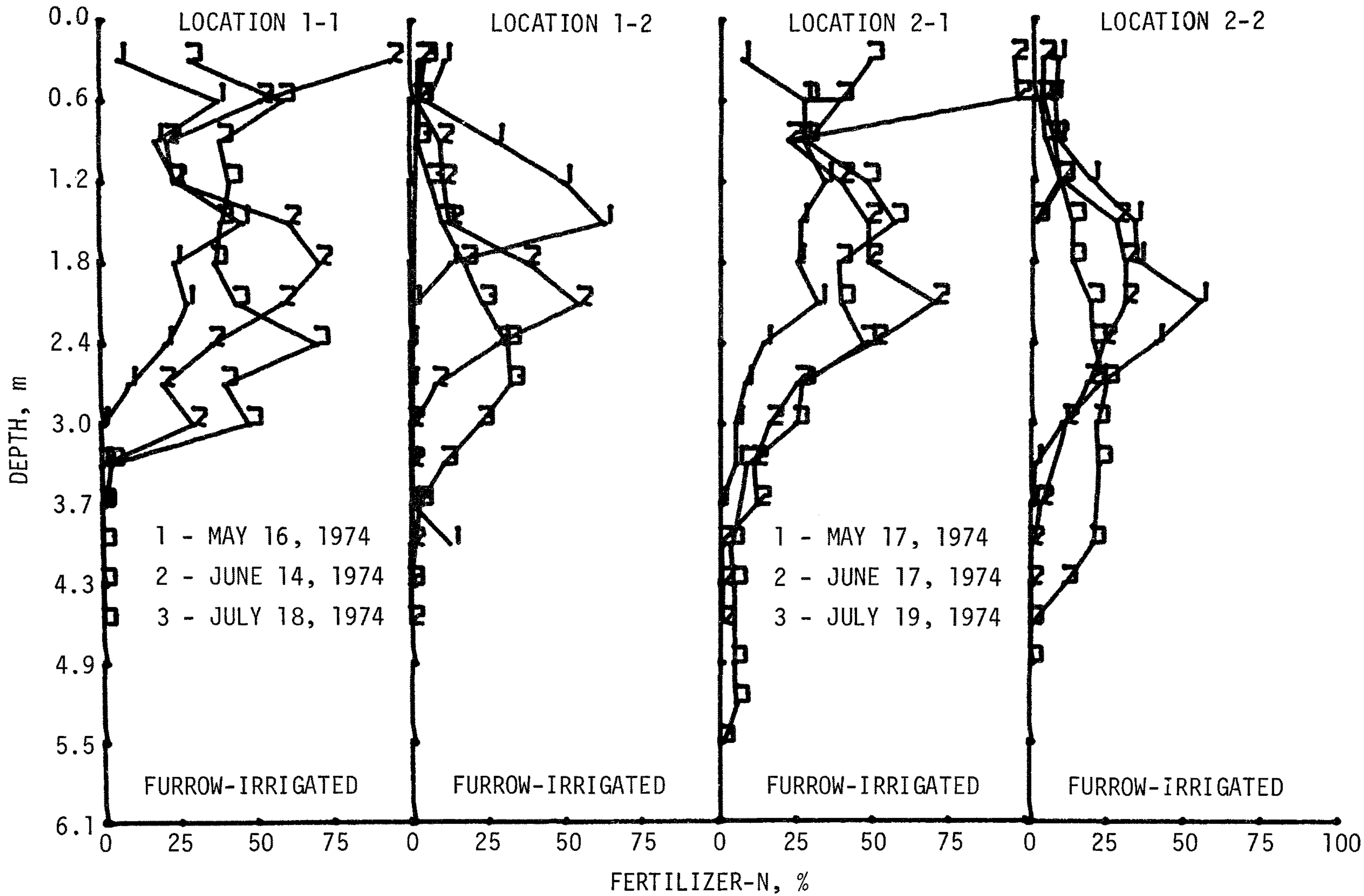


Figure 174. Percent nitrate-N from fertilizer by depth in 1974 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

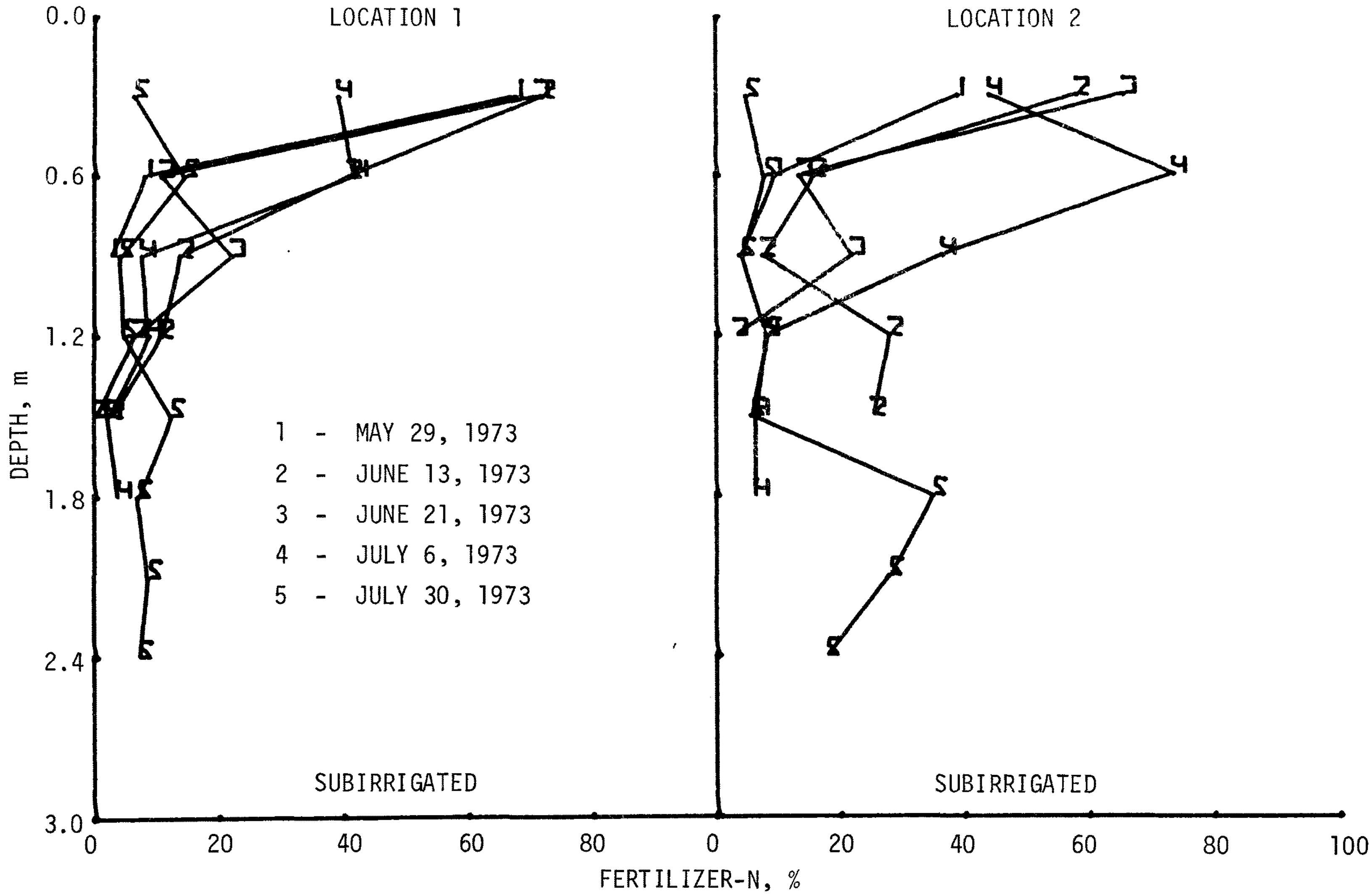


Figure 175. Percent nitrate-N from fertilizer by depth in 1973 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

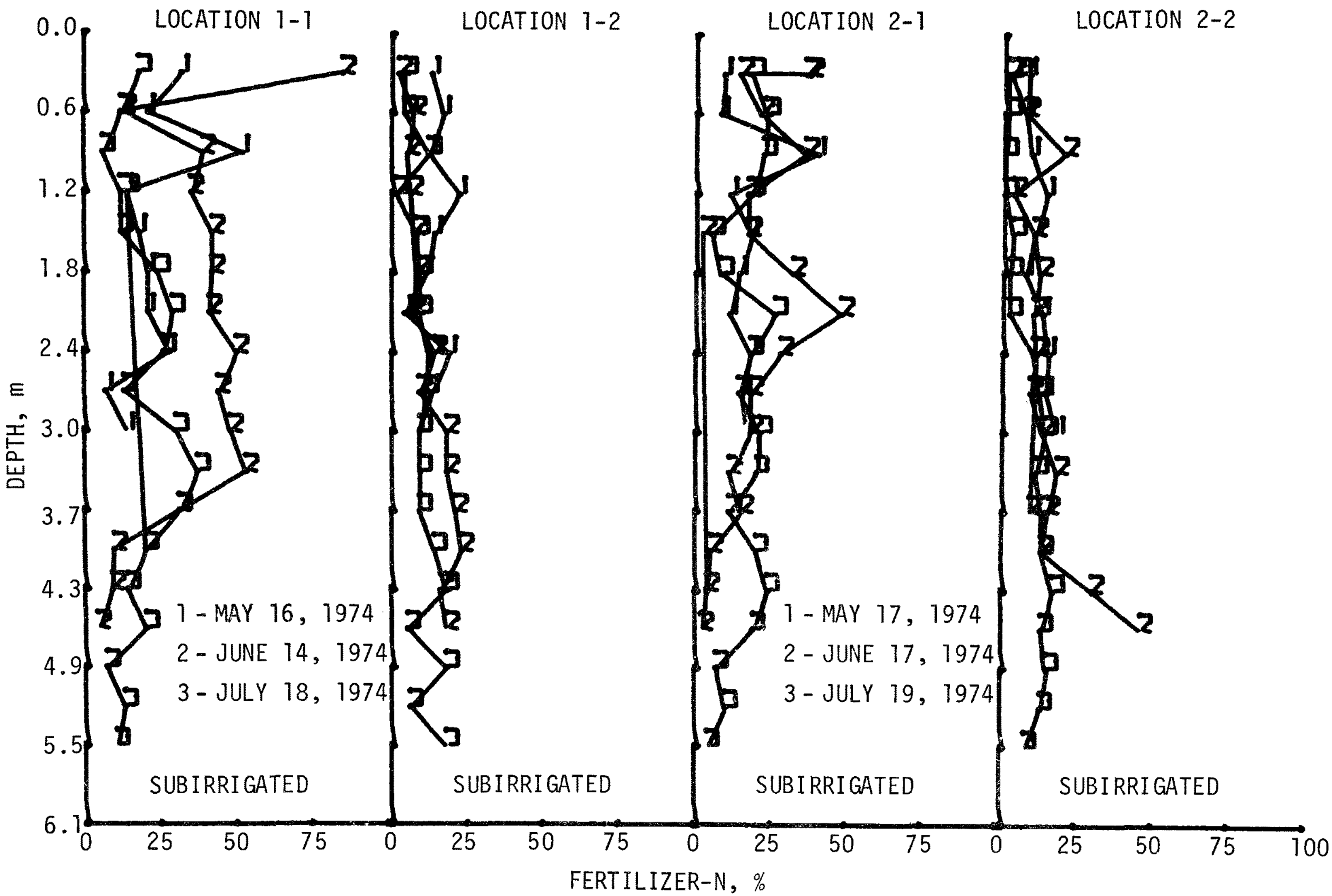


Figure 176. Percent nitrate-N from fertilizer by depth in 1974 for plots treated with ^{15}N-enriched sodium nitrate banded in the bed.

Analyses of data showing the contribution of fertilizer nitrogen to soil nitrate-N further supported the conclusions that leaching of fertilizer nitrogen occurred between seasons in the sprinkler-irrigated plot, during the season in the furrow-irrigated plot, and all but disappeared from the subirrigated plot that was not fertilized with ^{15}N-enriched fertilizer in 1974.

Data on the percentage of fertilizer nitrate-N emphasized the potential pollution from the various systems. Over 50% of the nitrogen at 2.4 to 3.0 m in the sprinkler plot at the beginning of the 1974 season and at 1.5 to 3.0 m in the furrow-irrigated plots during the growing season was fertilizer nitrogen, thus indicating a strong possibility that irrigation return flows with these systems can be degraded by fertilizer nitrogen even with good irrigation and fertilization practices.

Fertilizer nitrate-N percentages were high in one of the subirrigated plots but concentrations were too low to be of concern. However, the possibility of some leaching losses from subirrigation systems was found to be possible. The extremely low values obtained with the subirrigation system will be discussed in more detail in another section.

Leaching losses were found to be possible, especially with the furrow and sprinkler irrigation systems. However, the low concentrations obtained indicated that unless excess amounts of nitrogen are present when leaching occurs, the losses will be minimal.

Quantitative Studies--

At the end of two crop years (1973 and 1974), it was possible to account for 92.6%, 86.1%, and 50.5% of the fertilizer nitrogen applied to the sprinkler, furrow, and subirrigation systems, respectively. These calculations were based on fertilizer nitrogen found in above ground plant samples (Table 24) and soil samples taken to 5.2 m (Table 25). Soil samples were taken in 30-cm depth increments at five locations laterally across the beds as previously described. A weighted average was obtained for each depth using the relative contribution of each lateral sample to a given horizontal soil layer 30-cm thick. Actual bulk densities were used in converting to kilograms per hectare.

Fertilizer was applied to the plots used in this study for the first time in 1973 during the course of this project. That year, the greatest quantity of fertilizer nitrogen was taken up on the sprinkler plots and least on the subirrigated plots (Table 26). While this resulted in a substantially greater percentage of fertilizer nitrogen being incorporated into plant material in sprinkler than subirrigated plots, as a percentage of total nitrogen in the crop, there were no differences. Plant residue from the 1973 crop was returned to the soil.

Total fertilizer nitrogen recovered from fertilizer applied in both 1973 and 1974 in the above ground plant material by the 1974 crop was 56.5, 72.4, and 62.9 kg/ha which represented 62.2%, 55.2%, and 49.3% of the total nitrogen taken up for the sprinkler, furrow, and subirrigation systems, respectively. The breakdown of the source of this fertilizer nitrogen is

TABLE 24. PLANT GROWTH AND NITROGEN DATA FOR THE TOP GROWTH OF SPRINKLER-IRRIGATED SWEET CORN GROWN ON PLOTS FERTILIZED TWO YEARS WITH ^{15}N-ENRICHED SODIUM NITRATE, 1974

1974 Date		Plant wt, g	Total N, %	N/plant, g	Total N, kg/ha	N from fertilizer, %	N from fertilizer, kg/ha	N from soil, kg/ha
					Plot 6 - Location 1			
May 22		0.68	2.10	0.014	0.643	41.97	0.270	0.373
June 18		44.57	2.02	0.901	41.396	76.54	31.685	10.349
June 25		67.64	1.72	1.160	53.296	78.24	41.698	11.592
July 17	Plant	110.58	1.04	1.149	52.791	75.59	39.906	12.891
	Grain	18.49	1.75	0.324	14.885	76.25	11.346	3.539
	Total	129.07			67.676		51.252	16.430
					Plot 6 - Location 2			
May 22		1.19	2.30	0.027	1.240	41.81	0.515	0.717
June 18		66.14	1.65	1.094	50.264	55.37	27.832	22.445
June 25		102.51	1.38	1.419	65.196	60.42	39.390	25.816
July 17	Plant	99.14	1.24	1.233	56.651	53.20	30.139	29.882
	Grain	70.97	1.76	1.251	57.480	54.99	31.606	25.872
	Total	170.11			114.131		61.745	55.754
					Plot 18 - Location 1			
May 20		0.75	3.06	0.022	0.977	48.63	0.470	0.504
June 19		47.50	1.94	0.920	40.851	52.28	21.358	19.477
June 25			S A M P L E	L O S T	I N	D R Y I N G		
July 17	Plant	153.64	1.17	1.795	79.705	60.44	48.171	31.539
	Grain	59.74	2.06	1.232	54.708	64.04	35.034	19.678
	Total	213.38			134.413		83.205	51.217
					Plot 18 - Location 2			
May 21		1.00	3.05	0.031	1.354	36.41	0.493	0.862
June 20		147.13	2.04	2.999	133.169	59.76	79.587	53.581
June 25		96.15	1.66	1.596	70.869	60.94	43.187	27.664
July 17	Plant	110.76	1.48	1.642	72.912	50.32	36.691	36.243
	Grain	56.21	2.20	1.237	54.929	45.47	24.976	29.960
	Total	166.97			127.841		61.667	66.203
					Plot 32 - Location 1			
May 16		0.50	2.40	0.012	0.485	21.65	0.101	0.381
June 13		24.67	1.75	0.431	17.410	33.58	5.846	11.558
June 25		76.74	1.54	1.183	47.787	53.67	25.648	22.154
July 18	Plant	75.45	0.98	0.742	29.972	39.95	11.973	18.010
	Grain	62.47	1.51	0.945	38.175	34.15	13.418	24.763
	Total	137.92			68.147		25.391	42.773
					Plot 32 - Location 2			
May 17		0.48	2.40	0.011	0.444	37.05	0.168	0.280
June 14		24.53	1.80	0.442	17.854	43.41	7.750	10.114
June 25		68.45	1.76	1.202	48.554	67.86	32.950	15.613
July 19	Plant	246.22	1.01	2.481	100.222	53.96	54.085	46.144
	Grain	126.13	1.70	2.144	86.610	53.39	46.245	40.365
	Total	372.35			186.832		100.330	86.509

TABLE 25. FERTILIZER NITROGEN FOUND IN TWO NITROGEN FRACTIONS OF SOIL SAMPLES FROM PLOTS FERTILIZED TWO YEARS WITH ^{15}N-ENRICHED SODIUM NITRATE AND CROPPED WITH SWEET CORN IRRIGATED BY THREE SYSTEMS, LOCATION 1

Sample depth, m	Irrigation system					
	Sprinkler		Furrow		Subirrigation	
	NO_3^--N	Organic N	NO_3^--N	Organic N	NO_3^--N	Organic N
	kg/ha					
0.3	4.0	42.2	7.6	15.3	7.3	11.1
0.6	19.7	21.2	15.9	3.4	0.8	1.5
0.9	16.8	9.4	10.4	0.8	0.2	6.2
1.2	7.2	13.0	18.5	12.1	0.8	0.6
1.5	2.0		11.0		0.6	
1.8	1.2		8.7		2.0	
2.1	2.1		16.4		2.3	
2.4	4.1		16.2		2.3	
2.7	10.8		6.4		0.7	
3.0	14.0		2.0		3.0	
3.4	6.6		0.5		4.1	
3.7	1.6		0.0		3.0	
4.0	0.6		0.0		1.6	
4.3	0.2		0.0		1.0	
4.6	0.0		0.0		1.5	
4.9	0.0		0.0		1.2	
5.2	0.0		0.0		0.8	
Total	90.9	85.8	113.6	31.6	33.2	19.4

given in Table 27. The percent of total nitrogen in the 1974 crop that was applied as fertilizer in 1973 ranged from 2.0%, 3.6%, and 7.4%, respectively, for the furrow, sprinkler, and subirrigation plots. The large differences between irrigation systems observed in fertilizer nitrogen incorporated into above ground plant material in 1973 were not found in 1974. Also, in contrast to 1973, substantial differences were found between irrigation systems with respect to the percentage of the total nitrogen in the crop that was from the 1974 fertilizer application.

Examples of plant growth and nitrogen uptake patterns are shown in Figures 177, 178, and 179, respectively, for a sprinkler plot in 1973 and a subirrigation plot in 1973 and 1974. The uptake and growth curves are typical for growth and nitrogen uptake. The curves were different between years probably due to differences between hybrids and growing seasons.

The largest differences between irrigation systems in accounting for the fertilizer nitrogen applied during the two years occurred in the soil rather

TABLE 26. PLANT GROWTH AND NITROGEN DATA FOR THE TOP GROWTH OF SPRINKLER-IRRIGATED SWEET CORN FERTILIZED WITH ^{15}N-ENRICHED SODIUM NITRATE, 1973

1973 Date		Plant wt, g	Total N, %	N/plant, g	Total N, kg/ha	N from fertilizer, %	N from fertilizer, kg/ha	N from soil, kg/ha
					Plot 6 - Location 1			
May 21		0.68	2.09	0.014	0.897	67.68	0.607	0.290
May 29		3.38	1.97	0.067	4.185	90.64	3.793	0.392
June 13		57.25	1.92	1.099	69.102	77.86	53.803	15.289
June 21		88.75	1.23	1.092	68.625	67.74	46.487	22.139
July 5		133.53	1.00	1.335	83.944	79.28	66.550	17.394
July 30	Plant	107.55	1.07	1.151	72.345	65.94	47.704	24.641
	Grain	60.84	1.84	1.195	70.375	59.67	41.993	28.382
	Total	168.39			142.720		89.697	53.023
Population: 62,900 plants/ha								
					Plot 6 Location 2			
May 21		0.76	2.90	0.022	1.478	60.91	0.900	0.323
May 29		3.41	2.50	0.085	5.706	94.56	5.395	0.310
June 13		62.48	2.50	1.612	107.834	66.71	71.935	35.898
June 22		99.79	1.63	1.627	108.810	79.71	86.733	22.077
July 5		145.73	1.23	1.792	119.908	86.12	103.265	16.643
July 30	Plant	116.32	1.08	1.256	84.038	72.28	60.743	23.295
	Grain	67.45	1.87	1.261	84.373	58.69	49.519	34.854
	Total	183.77			168.411		110.262	58.149
Population: 66,900 plants/ha								
					Plot 18 - Location 1			
May 21		1.31	1.48	0.019	1.137	35.19	0.400	0.737
May 29		2.82	2.60	0.073	4.294	59.31	2.547	1.747
June 11		61.84	1.87	1.156	67.742	74.51	50.475	17.267
June 22		92.68	1.81	1.677	98.269	69.25	68.051	30.218
July 6		169.96	0.69	1.727	101.180	71.61	72.455	28.725
July 30	Plant	138.26	0.91	1.258	73.706	75.21	55.434	18.272
	Grain	69.48	2.02	1.403	82.218	69.76	57.355	24.863
	Total	207.74			155.924		112.789	43.135
Population: 58,600 plants/ha								
					Plot 18 - Location 2			
May 21		0.88	1.94	0.017	0.955	0.59	0.006	0.950
May 29		2.15	2.45	0.053	2.944	74.46	2.193	0.752
June 11		49.22	2.10	1.034	57.756	71.61	41.359	16.397
June 22		69.69	1.68	1.171	65.424	78.53	51.377	14.046
July 5		135.27	0.95	1.285	71.810	46.20	33.177	38.634
July 30	Plant	108.92	0.91	0.991	55.387	69.33	38.400	16.987
	Grain	56.25	1.84	1.035	57.835	62.08	35.904	21.931
	Total	165.17			113.222		74.304	38.918
Population: 55,900 plants/ha								
					Plot 32 - Location 1			
May 21		0.63	2.70	0.017	1.043	79.71	0.831	0.213
May 29		3.39	2.21	0.075	4.567	80.83	3.692	0.876
June 13		51.33	2.25	1.155	70.429	51.98	36.609	33.821
June 21		93.97	1.40	1.316	80.229	58.27	46.750	33.480
July 5		123.03	1.48	1.821	111.038	59.21	65.746	45.293
July 30	Plant	114.12	0.83	0.947	57.763	67.88	39.209	18.554
	Grain	66.25	1.60	1.060	64.642	62.01	40.085	24.557
	Total	180.37			122.405		79.294	43.111
Population: 61,000 plants/ha								
					Plot 32 - Location 2			
May 21		0.72	2.50	0.018	1.011	74.25	0.750	0.260
May 29		4.71	2.53	0.119	6.661	72.77	4.847	1.813
June 13		44.94	2.23	1.002	56.002	49.64	27.800	28.203
June 21		54.18	2.50	1.354	75.688	68.12	51.559	24.129
July 5		128.13	1.10	1.409	78.756	53.08	41.804	36.952
July 30	Plant	101.80	0.86	0.875	48.922	71.17	34.817	14.104
	Grain	55.77	1.76	0.982	54.851	61.97	33.991	20.860
	Total	157.57			103.773		68.808	34.964
Population: 55,900 plants/ha								

TABLE 27. FERTILIZER NITROGEN DATA FOR THE TOP GROWTH OF TWO CROPS OF IRRIGATED SWEET CORN FERTILIZED WITH ^{15}N-ENRICHED SODIUM NITRATE*

Irrigation system	1973 Crop Fertilizer N kg/ha	1973 Crop Fertilizer N % of N applied	1973 Crop Fertilizer N % of N in crop	1974: 1973 Fertilizer N kg/ha	1974: 1973 Fertilizer N % of N applied	1974: 1973 Fertilizer N % of N in crop	1974: 1974 Fertilizer N kg/ha	1974: 1974 Fertilizer N % of N applied	1974: 1974 Fertilizer N % of N in crop
Sprinkler	100.0	80.9	64.3	3.0	2.4	2.0	53.5	51.0	58.8
Furrow	93.5	75.6	69.5	3.7	3.0	3.6	68.7	65.5	52.4
Subirrigation	74.0	59.8	65.6	6.3	5.1	7.4	56.6	54.0	44.4

* 123.7 lbs of N as sodium nitrate applied in 1973.
104.9 lbs of N as sodium nitrate applied in 1974.

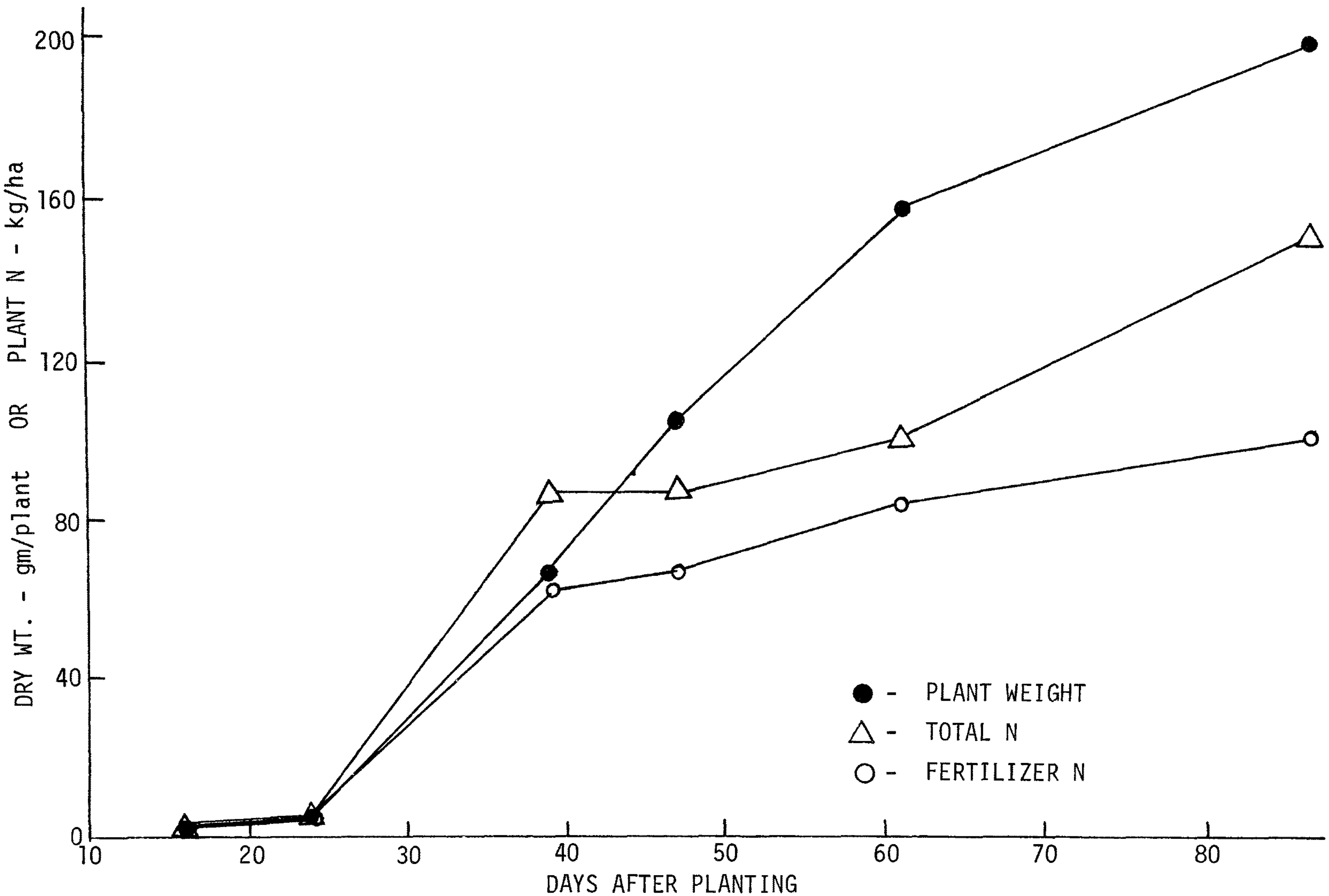


Figure 177. Dry matter production, total nitrogen, and fertilizer nitrogen in the tops of sprinkler-irrigated sweet corn fertilized with ^{15}N-enriched sodium nitrate, 1973.

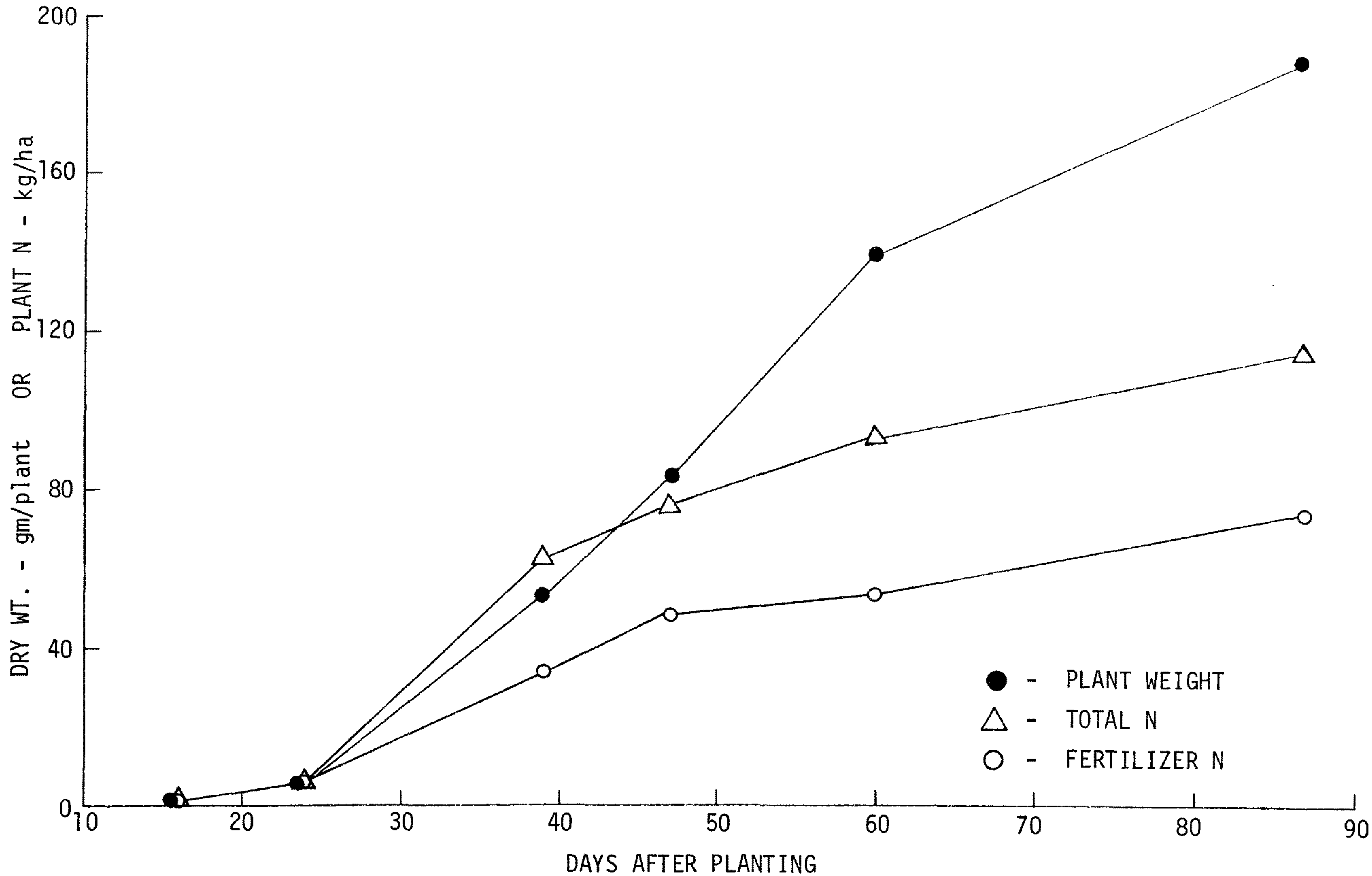


Figure 178. Dry matter production, total nitrogen, and fertilizer nitrogen in the tops of subirrigated sweet corn fertilized with ^{15}N-enriched sodium nitrate, 1973.

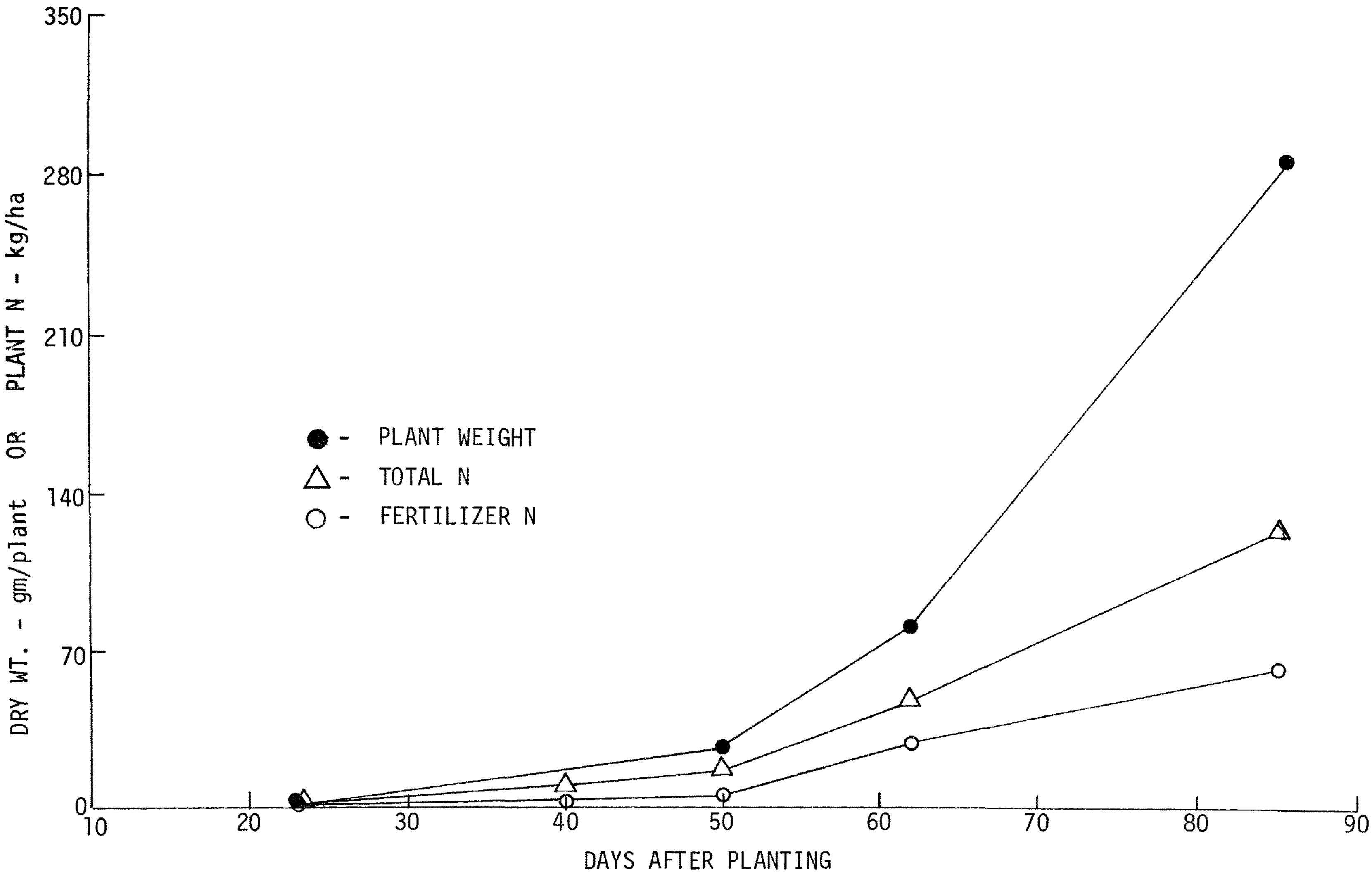


Figure 179. Dry matter production, total nitrogen, and fertilizer nitrogen in the tops of subirrigated sweet corn fertilized with ^{15}N-enriched sodium nitrate, 1974.

than the plants (Tables 25 and 27). Nitrate concentration peaks were found in the profile immediately above layers in which abrupt increases in sand percentages and/or lower bulk densities occurred. Particle-size distributions and bulk densities can be seen in Figures 10, 11, and 12, with discussion of effects on hydraulic conductivities beginning on page 39. For the sprinkler system, 176.7 kg of nitrogen/ha were found in the soil profile down to 5.2 m with 90.0 kg/ha as nitrate and 85.8 kg/ha as organic nitrogen. A significant amount of fertilizer nitrogen, 41.2 kg/ha, or 18% of that applied, was found below 1.5 m which is considered to be below the effective root zone for the crop grown. The amount of fertilizer nitrogen found in the soil under furrow irrigation was 145.2 kg/ha with 113.6 kg/ha nitrate and 31.6 in organic forms. While the total amount was less than that under sprinkler irrigation, more was in the nitrate form and more, 50.2 kg/ha, or 22% of that applied, was found below 1.5 m. Under subirrigation, much less fertilizer nitrogen was found in the soil profile. To a profile depth of 5.2 m, 52.6 kg of nitrogen/ha were found with 33.2 kg/ha as nitrate and 19.4 kg/ha as organic nitrogen. In addition, lesser amounts of fertilizer nitrogen, 23.5 kg/ha or 14.5% of applied, were found below 1.5 m. One interesting phenomena was the declining amount of fertilizer nitrogen found in organic forms in the irrigation system order of sprinkler > furrow > subirrigation. These data show irrigation return flow quality for these irrigation systems, as measured by fertilizer nitrate-N, to be in the order: subirrigation > sprinkler > furrow.

Since the amount of fertilizer nitrogen recovered in the plant material in 1974 for the subirrigation system was comparable to that of the other systems, the low percentage accountability for this system was a result of not finding the nitrogen in the soil. Nitrate-N concentrations under subirrigation have been low throughout this study when fertilizer was banded. Because of this, an independent study involving intensive sampling and bromide and nitrate fertilizer was conducted. This study is reported in the experimental section. All the available data point to the conclusion that the measurements are correct and that the soil profile under subirrigation contains less fertilizer nitrogen and the irrigation return flow will be of better quality from the standpoint of applied fertilizer than under sprinkler and furrow irrigation.

Disappearance of Nitrate From Subirrigated Plots

During the first two years of the project, relatively large amounts of nitrate-N were measured in the soil-water extracts from samples where the fertilizer was applied in the irrigation water in the subirrigated plots. However, in the control plots and in plots where fertilizer was banded above and to either side of the subirrigation lateral, only small amounts of nitrate-N were detected. Initially, it was thought that nitrate was not detected in these plots because of inadequate sampling. This may have been true for the samples taken early in the growing season, but other data obtained show this is not true for samples taken late in the season.

A preliminary study was conducted in 1972 to obtain data relative to the sampling technique on all three irrigation systems. In this particular study, sodium bromide was used along with sodium nitrate chiseled into both sides of the beds, as previously described and intensive samples taken every 12.7 cm laterally across the beds and down to a depth of 2.1 m. Data from these samples are given in Tables 28 through 39. In comparing the data in Tables 28 through 33, it is easy to see that concentrations of nitrogen were generally lower in the subirrigated plots (0 to 6.3 ppm, Tables 32 and 33) than the sprinkler- (0 to 27.7 ppm, Tables 28 and 29) or furrow- (0 to 12.8 ppm, Tables 30 and 31) irrigated plots. Also, the highest concentrations of nitrate-N in the sprinkler and furrow plots occurred at depths of 1.2 and 1.5 m whereas for the subirrigated plot highest concentrations occurred in the top 0.6 m of the profile. The bromide data in Tables 34 through 39 confirm the nitrate distribution found in the previous tables. It will be noted that for the subirrigated plots the concentrations of bromide were less than 1 ppm below 0.9 m and that concentrations up to 31 ppm occurred in the upper portion of the profile. It is of interest to note that in the sprinkler-irrigated plot (Table 28, Location 1) where the nitrate-N concentrations were generally low, the bromide concentrations show that nitrate did not move below a depth of 0.9 m (Table 34). Consequently, the nitrate applied with the bromide was probably taken up by the plants. These results for nitrate-N were typical of those obtained from the profiles of the various irrigation systems when fertilizer was banded and the measurements were made at the end of the season.

In addition to this test conducted in 1972, another test was conducted with a second crop. The soil-water extracts from porous bulbs for this crop are shown in Table 40. Cross-sectional samples from the top of one bed to the top of the next bed were taken at various dates after the application of fertilizer and while a crop was growing. Fertilizer was applied as a band 12.7 cm either side of the bed on July 27. A 76.2-mm irrigation was applied and the crop was planted. First measurements were made on July 28 and nitrate was found primarily in planes B and C. Subsequent samples taken on August 14 showed extremely high concentrations of nitrate-N in the top 45 cm of the profile in planes A, B, C, and D. Overall, concentrations tended to decrease in the top 45 cm until the last sampling date on October 2 in which all concentrations with the exception of one sample in the bottom of the furrow showed relatively low concentrations of nitrate-N compared to previous samples.

These data taken in conjunction with the data shown in Figures 180 through 182 for a ^{15}N tracer study conducted in 1973 show that the nitrogen applied as fertilizer in bands tended to move down the most in the sprinkler system early in the season, somewhat less in the furrow system and that the nitrate-N tended to remain in the upper portions of the profile for the subirrigation system.

Differences in the plant nitrogen uptake and growth curves (Figures 177, 178, and 179) showed less mid-season nitrogen uptake and growth by the subirrigated plots. However, the data in Tables 24 and 26 showing the total amount of fertilizer nitrogen taken up by the plants in both 1973 and 1974 again show little difference between systems in that the variations within a plot were generally as great or greater than the variations between irrigation systems.

TABLE 28. NITRATE-N CONCENTRATION (PPM) AT SELECTED DEPTHS FROM A SPRINKLER IRRIGATED PLOT (LOCATION 1) AT THE FIELD SITE NEAR MUNDAY, TEXAS, ON AUGUST 8, 1972

Depth,	Lateral distance, cm								
m	0.0	12.7	25.4	38.1	50.8	63.5	76.2	88.9	101.6
0.3	2.8	5.9	2.2	2.9	3.7		2.4	2.5	3.4
0.6	1.4	1.4	1.5	1.2	1.7	2.2	2.6	2.2	3.1
0.9	1.8	1.8	1.1	1.6	2.2	1.5	3.7	1.9	5.1
1.2	1.4	1.6	1.3	2.4	2.7	3.8	4.0	2.8	4.9
1.5	1.7	1.5	1.5	0.9	3.5	4.1	3.6	3.8	3.5
1.8	1.3	1.9	2.3	2.9	3.0	3.0	3.0	1.8	2.6
2.1	2.5	2.3	2.4	1.0	2.4	1.8	1.2	1.9	1.6

TABLE 29. NITRATE-N CONCENTRATION (PPM) AT SELECTED DEPTHS FROM A SPRINKLER IRRIGATED PLOT (LOCATION 2) AT THE FIELD SITE NEAR MUNDAY, TEXAS, ON AUGUST 8, 1972

Depth,	Lateral distance, cm								
m	0.0	12.7	25.4	38.1	50.8	63.5	76.2	88.9	101.6
0.3	2.4	3.1	2.8	2.2	1.2	7.4	3.1	4.8	3.9
0.6	2.9		2.5	2.2	1.2	2.4	2.5	1.9	2.3
0.9	2.4	2.3	1.8	1.2	1.9	1.9	1.2	2.1	2.6
1.2	3.1	11.5	27.7	4.4	3.2	4.9	2.4	1.8	1.4
1.5	9.8	21.6	21.1	6.8	4.6	12.3	11.7	3.5	1.8
1.8	4.5	7.8	6.8	4.8	4.2	6.8	9.4	6.8	7.5
2.1	2.6	2.7	3.9	4.5	3.9	4.2	3.4	6.0	7.9

TABLE 30. NITRATE-N CONCENTRATION (PPM) AT SELECTED DEPTHS FROM A FURROW-IRRIGATED PLOT (LOCATION 1) AT THE FIELD SITE NEAR MUNDAY, TEXAS, ON AUGUST 8, 1972

Depth, m	Lateral distance, cm								
	0.0	12.7	25.4	38.1	50.8	63.5	76.2	88.9	101.6
0.3	0.9	2.4	3.3	1.9	2.2	1.7	1.4	2.3	
0.6	1.1	0.5	1.2	1.5	0.9	1.5		1.2	1.2
0.9	3.5	5.1	2.1	1.6	1.2	1.9	1.4		1.7
1.2	13.8	12.8	4.6		2.8	4.0	3.0	3.4	4.5
1.5	8.3	9.7	4.6	2.1	7.2	8.3	12.3	13.0	12.8
1.8	3.2	3.6	3.2	3.5	3.7				
2.1	2.5	2.4	1.7	2.7	2.4				

TABLE 31. NITRATE-N CONCENTRATION (PPM) AT SELECTED DEPTHS FROM A FURROW-IRRIGATED PLOT (LOCATION 2) AT THE FIELD SITE NEAR MUNDAY, TEXAS, ON AUGUST 8, 1972

Depth, m	Lateral distance, cm								
	0.0	12.7	25.4	38.1	50.8	63.5	76.2	88.9	101.6
0.3	2.0	1.4	1.6	1.7	2.3	1.5	1.6	1.6	1.4
0.6	2.0	1.2	1.7	1.5	3.2	3.1	2.8	1.3	1.2
0.9	1.4	1.5	2.1	1.6	5.0	6.4	5.3	2.9	1.9
1.2	1.9	1.9	2.6	2.7	8.9	12.8	10.4	7.8	6.2
1.5	3.1	2.5	1.9	3.8	7.8	11.7	11.7	10.8	10.2
1.8	5.6	6.8	7.7	8.9	7.8	8.6	7.6	5.9	3.9
2.1	5.7	6.1	8.4	8.5	7.1	5.4	4.0		2.2

TABLE 32. NITRATE-N CONCENTRATION (PPM) AT SELECTED DEPTHS FROM A SUB-IRRIGATED PLOT (LOCATION 1) AT THE FIELD SITE NEAR MUNDAY, TEXAS, ON AUGUST 8, 1972

Depth, m	Lateral distance, cm								
	0.0	12.7	25.4	38.1	50.8	63.5	76.2	88.9	101.6
0.3	3.2	2.1	2.5	2.8	2.1	1.8	1.6	1.4	0.8
0.6	6.3	4.5	2.2	1.9	1.7	1.4	1.3	1.4	1.8
0.9	4.5	6.8	1.8	1.0	0.5	0.3	1.5	1.1	0.9
1.2	1.9	2.3	2.2	1.6	1.4	0.5	1.1	1.5	1.6
1.5	2.0	2.0	2.5	2.1	1.7	1.1	0.9	1.9	1.4
1.8	1.8	2.5	2.9	3.8	3.4	1.2	1.3	1.0	1.1
2.1	2.3	2.6	2.6	3.4	3.0	1.6	1.2	1.1	1.2

TABLE 33. NITRATE-N CONCENTRATION (PPM) AT SELECTED DEPTHS FROM A SUB-IRRIGATED PLOT (LOCATION 2) AT THE FIELD SITE NEAR MUNDAY, TEXAS, ON AUGUST 8, 1972

Depth, m	Lateral distance, cm								
	0.0	12.7	25.4	38.1	50.8	63.5	76.2	88.9	101.6
0.3	1.3	1.5	1.9	1.4	1.6	1.6	2.3	1.3	1.6
0.6	1.3	1.7	1.2	1.3	1.7	1.4	1.7	2.2	1.6
0.9	1.5	1.7	1.8	1.5	1.5	1.8	1.7	1.6	1.5
1.2	0.8	1.5	1.5	1.3	1.8	1.5	1.5	1.6	1.3
1.5	1.6	1.4	1.6	1.3	1.9	1.3	1.7	1.1	0.8
1.8	1.8	2.0	1.8	2.0	2.7	2.2	1.5	1.4	1.5
2.1	1.5	1.4	1.7	1.7	2.0	2.1	1.4	1.4	1.2

TABLE 34. BROMIDE CONCENTRATION (PPM) AT SELECTED DEPTHS FROM A SPRINKLER-IRRIGATED PLOT (LOCATION 1) AT THE FIELD SITE NEAR MUNDAY, TEXAS, ON AUGUST 8, 1972

Depth, m	Lateral distance, cm								
	0.0	12.7	25.4	38.1	50.8	63.5	76.2	88.9	101.6
0.3	2.4	1.1	2.8	1.2	1.2	1.5	1.7	1.1	0.8
0.6	0.5	0.8	0.1	0.0	0.2	0.0	0.0	0.0	0.0
0.9	1.0	8.8	7.1	0.0	0.2	12.2	9.9	1.1	0.0
1.2	0.0	0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.6
1.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
1.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.1	0.0	0.0	0.0	0.2	0.0	0.1	0.2	0.0	0.0

TABLE 35. BROMIDE CONCENTRATION (PPM) AT SELECTED DEPTHS FROM A SPRINKLER-IRRIGATED PLOT (LOCATION 2) AT THE FIELD SITE NEAR MUNDAY, TEXAS, ON AUGUST 8, 1972

Depth, m	Lateral distance, cm								
	0.0	12.7	25.4	38.1	50.8	63.5	76.2	88.9	101.6
0.3	0.2	0.7	0.1	0.3	0.5	3.5	0.8	3.6	3.1
0.6	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.9	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0
1.2	0.7	2.7	9.1	0.2	0.0	0.1	0.0	0.0	0.0
1.5	2.5	6.6	7.5	1.2	0.2	1.8	3.1	0.0	0.0
1.8	1.0	1.3	0.3	0.2	0.4	15.9	2.2	6.1	4.8
2.1	0.0	0.2	0.2	0.1	0.1	0.3	0.7	4.6	6.1

TABLE 36. BROMIDE CONCENTRATION (PPM) AT SELECTED DEPTHS FROM A FURROW-IRRIGATED PLOT (LOCATION 1) AT THE FIELD SITE NEAR MUNDAY, TEXAS, ON AUGUST 8, 1972

Depth, m	Lateral distance, cm								
	0.0	12.7	25.4	38.1	50.8	63.5	76.2	88.9	101.6
0.3	0.2	0.0	0.1	0.0	0.0	0.1	0.9	0.8	
0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.1
0.9	0.2	0.0	0.0	0.1	0.0	0.0	0.1	0.2	0.3
1.2	2.1	0.4	0.0		0.9	0.0	0.1	1.3	2.9
1.5	0.0	0.2	0.1	1.3	1.7	3.7	10.6	11.5	11.5
1.8	0.0	0.0	0.0	0.0	0.3				
2.1	0.0	0.0	0.0	0.0	0.6				

TABLE 37. BROMIDE CONCENTRATION (PPM) AT SELECTED DEPTHS FROM A FURROW-IRRIGATED PLOT (LOCATION 2) AT THE FIELD SITE NEAR MUNDAY, TEXAS, ON AUGUST 8, 1972

Depth, m	Lateral distance, cm								
	0.0	12.7	25.4	38.1	50.8	63.5	76.2	88.9	101.6
0.3	7.6	0.9	1.0	0.6	1.3	0.6	1.0	0.7	0.6
0.6	0.5	0.4	0.1	0.1	0.1	0.9	0.3	0.6	0.4
0.9	0.6	0.1	0.1	0.5	1.2	1.3	0.4	0.1	0.4
1.2	0.0	0.2	0.1	0.0	0.0	0.7	0.9	0.1	0.5
1.5	2.0	0.8	0.7	0.2	0.3	2.8	0.8	0.2	0.2
1.8	2.5	2.1	2.8	2.2	0.3	0.2	0.0	0.0	0.0
2.1	2.8	2.2	3.2	3.0	1.2	0.3	0.0		0.0

TABLE 38. BROMIDE CONCENTRATION (PPM) AT SELECTED DEPTHS FROM A SUB-IRRIGATED PLOT (LOCATION 1) AT THE FIELD SITE NEAR MUNDAY, TEXAS, ON AUGUST 8, 1972

Depth, m	Lateral distance, cm								
	0.0	12.7	25.4	38.1	50.8	63.5	76.2	88.9	101.6
0.3	7.8	3.8	2.0	3.9	2.9	1.3	1.1	0.9	0.4
0.6	31.4	4.0	1.9	1.3	0.0	0.8	0.0	0.3	0.1
0.9	11.2	7.6	1.0	0.3	0.8	0.9	0.1	0.2	0.2
1.2	0.4	1.2	0.2	0.0	0.0	1.3	0.0	0.0	0.0
1.5	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
1.8	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 39. BROMIDE CONCENTRATION (PPM) AT SELECTED DEPTHS FROM A SUB-IRRIGATED PLOT (LOCATION 2) AT THE FIELD SITE NEAR MUNDAY, TEXAS, ON AUGUST 8, 1972

Depth, m	Lateral distance, cm								
	0.0	12.7	25.4	38.1	50.8	63.5	76.2	88.9	101.6
0.3	0.8	0.7	2.0	1.3	0.5	0.5	3.0	2.2	1.3
0.6	0.0	0.0	1.8	1.8	1.0	0.4	0.1	0.0	0.0
0.9	0.0	0.0	0.0	0.1	0.1	0.3	0.0	0.0	0.0
1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.1	0.0	0.0	0.0	0.5	0.0	0.4	0.0	0.0	0.7

TABLE 40. NITROGEN CONCENTRATIONS (PPM) OF SOIL-WATER EXTRACTS FROM POROUS BULB SAMPLES. SUB-IRRIGATED PLOT, 1972

		Plane*									
		A		B		C		D		E	
Date	Depth, m	NO_3^--N	NH_4^+-N	NO_3^--N	NH_4^+-N	NO_3^--N	NH_4^+-N	NO_3^--N	NH_4^+-N	NO_3^--N	NH_4^+-N
		ppm									
July 28	0.15	24	6	23	8	92	16	31	2	12	17
	0.30	6	0	42	1	15	1	7	0	7	3
	0.46	17	0	23	0			6	0	6	1
	0.61	7	2	13	0	37	2	10	3	6	1
	0.91	8	0	21	38	57	6	7	13	16	8
	1.22	9	3	6	6	25	3	4	6	5	1
	1.52	10	10	5	35	9	1	9	1	9	1
Aug. 14	0.15	810	189	16	7	130	1	180	69	7	4
	0.30	180	51	160	1	32	1	83	1	16	1
	0.46	170	2	99	2			21	0	8	5
	0.61	14	1	15	1	78	1	14	1	12	4
	0.91	9	0	33	26						
	1.22	11	1			26	2	7	4	12	2
Aug. 28	0.15	267	67	6	2	19	3	160	50	33	4
	0.30	86	1	27	1	27	1	25	3	12	1
	0.46	240	1	170	4			135	0	22	1
	0.61	97	2	110	2	40	2	150	1	26	5
Sept. 6	0.15	20	12	6	1	6	2	27	6	1	1
	0.30	10	3	7	1	4	2	17	0	2	1
	0.46	27	1	82	2			51	1	10	5
	0.61	27	1	67	4	71	2	99	1	6	2
	0.91	13	2	24	7	81	8	36	10		
	1.22	12	1	20	4	30	2	16	4	18	2
	1.52			38	8						
Sept. 14	0.15	73	21	8	1	9	1	6	1	1	1
	0.30	4	0	18	1	19	1	110	1	3	1
	0.46			51	1			16	1	4	1
	0.61	11	1	46	2	73	2	83	1	4	2
	1.22			26	0	37	4			8	2
Sept. 21	0.15	170	4	52	1	12	3	110	13	105	2
	0.30	16	12	18	1	17	1	11	1	1	1
	0.46			31	1			1	0	2	1
	0.61	7	2	23	2	52	1	35	1	1	1
	0.91			18	10						
	1.22	27	1	33	5	65	2	21	4	8	1
Oct. 2	0.15	10	11	19	1	15	13	93	15		
	0.30	1	2	4	1	13	2	5	0	2	2
	0.46			18	2			5	1	2	2
	0.61	2	8	11	3	40	2	9	4	3	2
	1.22					70	10			6	5

* Plane A is below the top of the bed;
Plane B, side of the bed or 25.4 cm from the top of the bed;
Plane C, furrow or 50.8 cm from the top of the bed;
Plane D, side of adjacent bed or 25.4 cm from the top of the adjacent bed;
Plane E, top of adjacent bed.

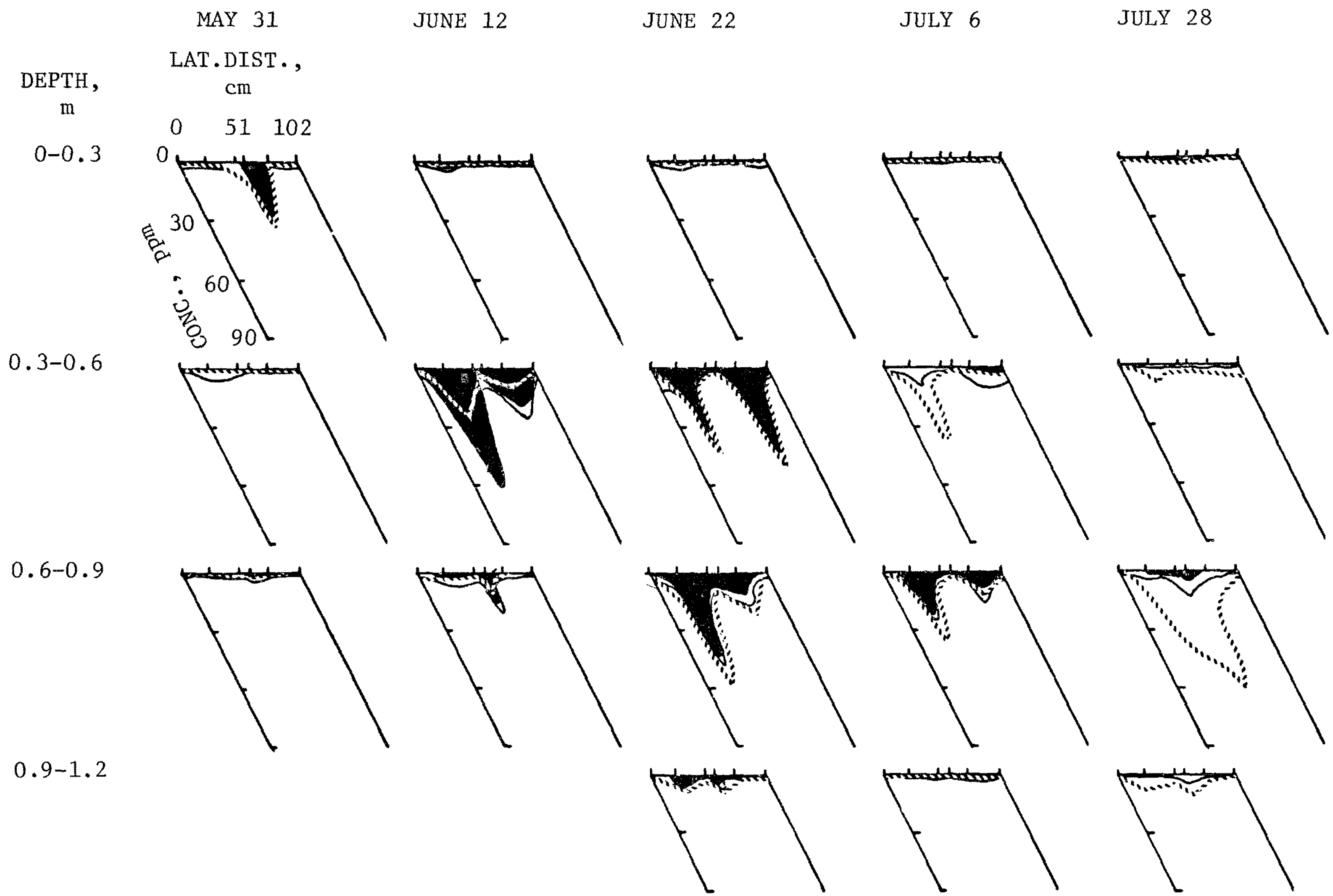


Figure 180. Lateral and vertical distribution of nitrate-N (———), fertilizer-N (━━━) and bromide (||||||||||) by date in soil sample extracts from Plot 6-1. (Sprinkler-irrigated - fertilized with ^{15}N-enriched sodium nitrate)

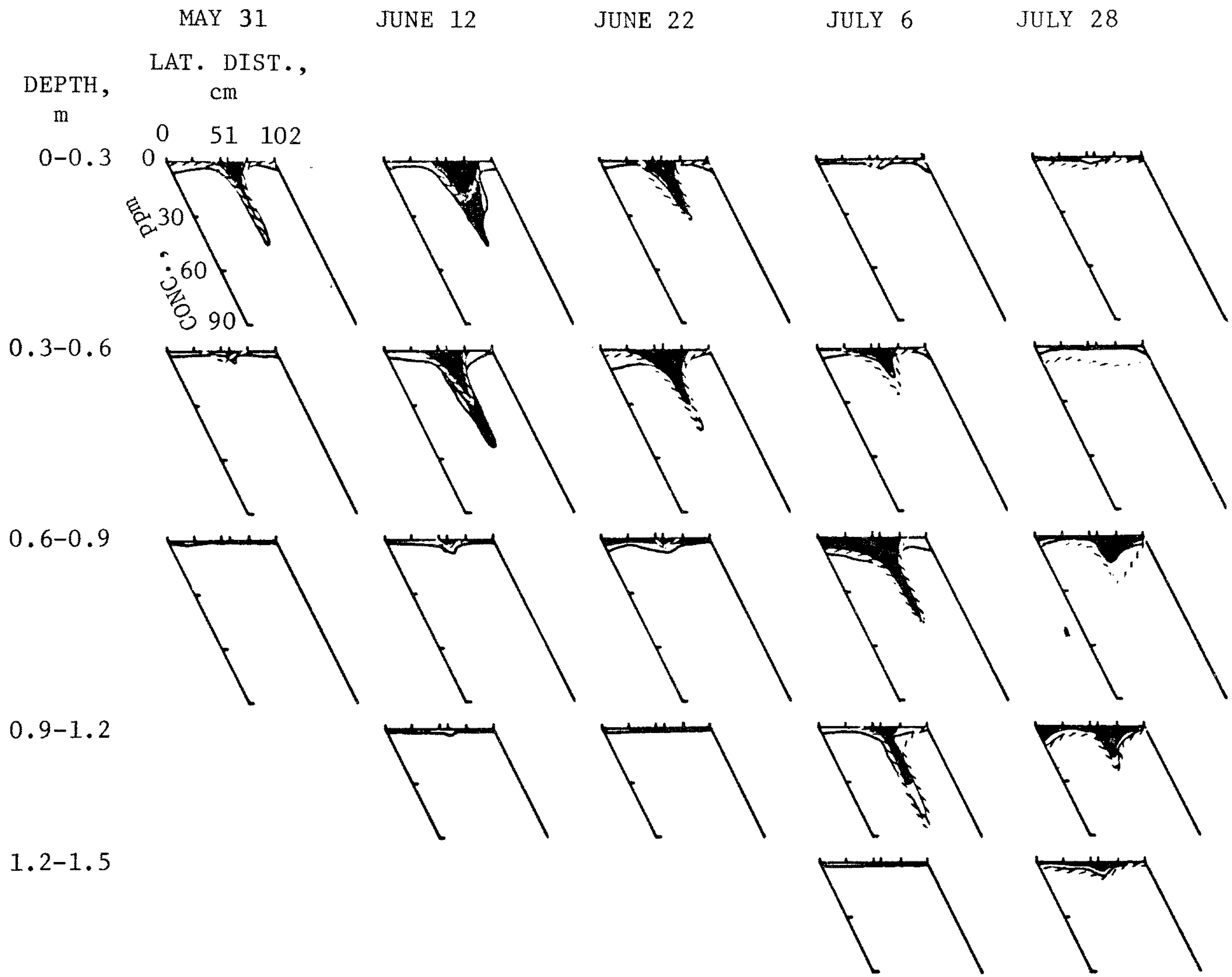


Figure 181. Lateral and vertical distribution of nitrate-N (———), fertilizer-N (▬▬) and bromide (\\\\\\\\) by date in soil sample extracts from Plot 18-1. (Furrow-irrigated - fertilized with ^{15}N-enriched sodium nitrate)

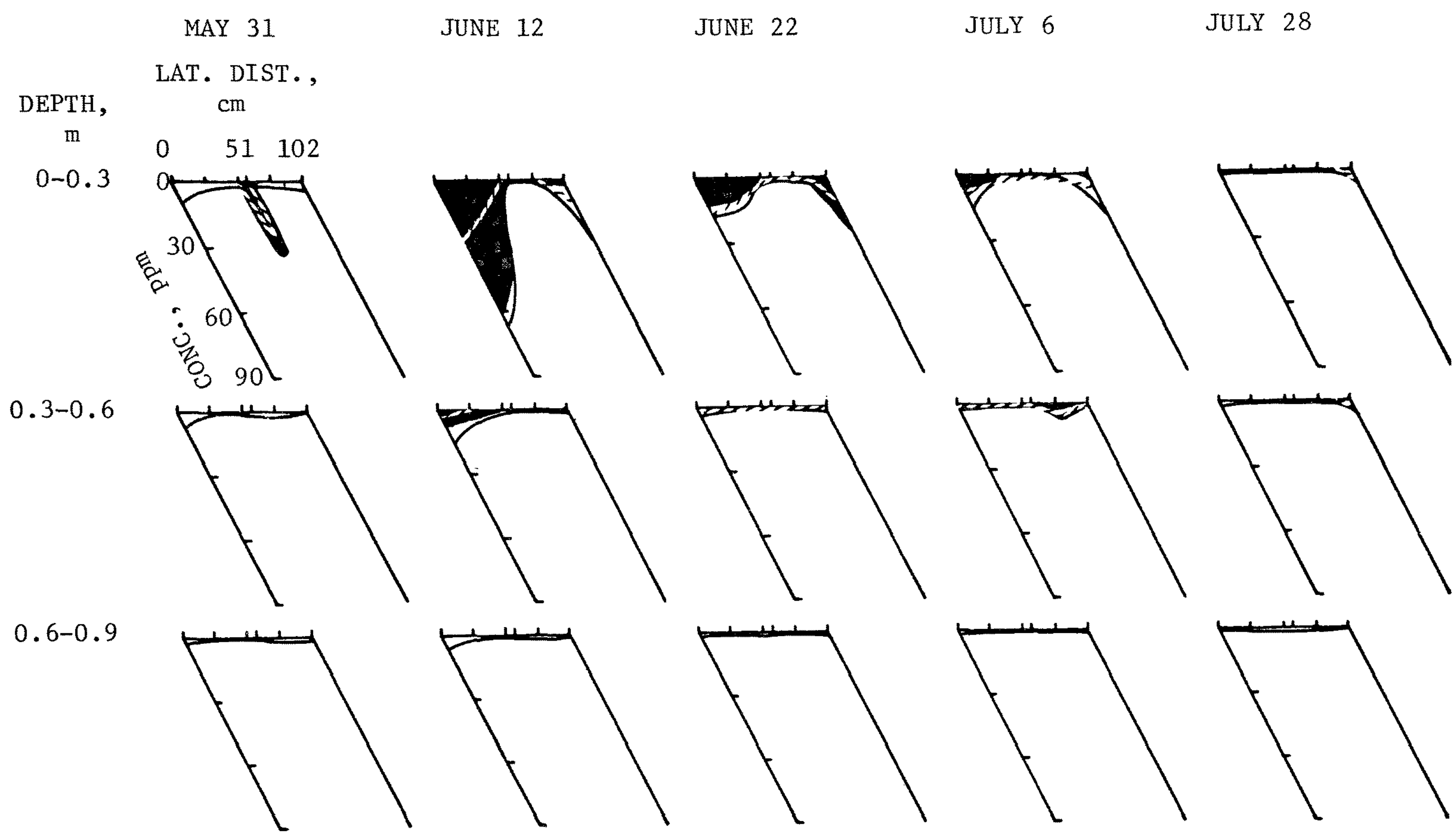


Figure 182. Lateral and vertical distribution of nitrate-N (———), fertilizer-N (▬▬) and bromide (////////) by date in soil sample extracts from Plot 32-1. (Subirrigated - fertilized with ^{15}N-enriched sodium nitrate)

Data from these same ^{15}N plots in 1974 show that approximately two weeks after the application of the banded fertilizer material on June 6 that in the top 0.3 m of soil the sprinkler plot contained 53 kg of nitrate-N/ha, the furrow plot 64.4 and the subirrigated plots 81.2, showing again that the subirrigated plots kept more nitrate-N in the upper part of the profile longer than did the furrow system which kept it there longer than did the sprinkler system.

The data in Table 25 show that in the process of accounting for the amount of nitrogen applied as fertilizer in 1973 and 1974 using ^{15}N as a tracer that of this nitrogen, 85.8 kg/ha was found in the organic form under the sprinkler plots, 31.6 kg/ha in the organic form under the furrow plots, and 19.4 kg/ha under the subirrigated plots. This indicates, since the crop residue was all applied to the soil and the amounts of fertilizer nitrogen actually removed by the plant material in 1973 were not that greatly different between the systems, that this organic residue must have been broken down and the nitrogen released into the soil from the organic fraction to a much greater extent in the subirrigated than in the furrow or in the sprinkler plots.

Water potential data at the 0.3-m level in the soil are given in Figures 183, 184, and 185 for the plots that were intensively sampled using both bromide and nitrate, for the subirrigated plots used in the second crop in 1972, and for the ^{15}N plots for 1974. Figure 185 for the ^{15}N plots in 1974 shows that the subirrigated plots at the 0.3-m depth had a potential of -10 cb or more throughout the growing season. It can be seen that the potential was lower in the furrow- and sprinkler-irrigated plots than in the subirrigated plots during the growing season at this depth. Much the same trend can be seen for the second crop in 1972 (Figure 184) with the subirrigated and furrow plots being somewhat closer together in the amount of time that a potential >-10 cb existed at the 0.3-m depth in the soil. In contrast to this, the data in Figure 183 show that the subirrigated and furrow-irrigated plots had water potentials >-10 cb above field capacity more of the time than did the sprinkler plots. Bremner and Shaw (2) have pointed out that losses to denitrification may occur when the soil moisture is greater than 60% of the water-holding capacity. The subirrigation systems in this study had 100% of the water-holding capacity much of the growing season.

This combination of factors, i.e., holding the nitrate-N up in the profile in conjunction with water potentials at or near field capacity for substantial portions of the growing season apparently resulted in a process of denitrification which then resulted in the loss of the nitrate-N from the profile into the atmosphere. The necessity for keeping the nitrate-N in the upper portion of the profile is of course shown by the distribution patterns of nitrate under sprinkler and furrow systems and the accountability of the amount of nitrogen applied as fertilizer in 1973 and 1974 in the ^{15}N tracer plots. In this particular study, it was found that it was possible to account for 92.6%, 86.1%, and 50.5% of the fertilizer nitrogen applied to the sprinkler, furrow, and subirrigation systems, respectively. Thus, practically all of the nitrogen could be accounted for over a two-year period that was applied as fertilizer for the sprinkler plots. It is possible that part of the nitrogen not accounted for did leave the soil by a process of

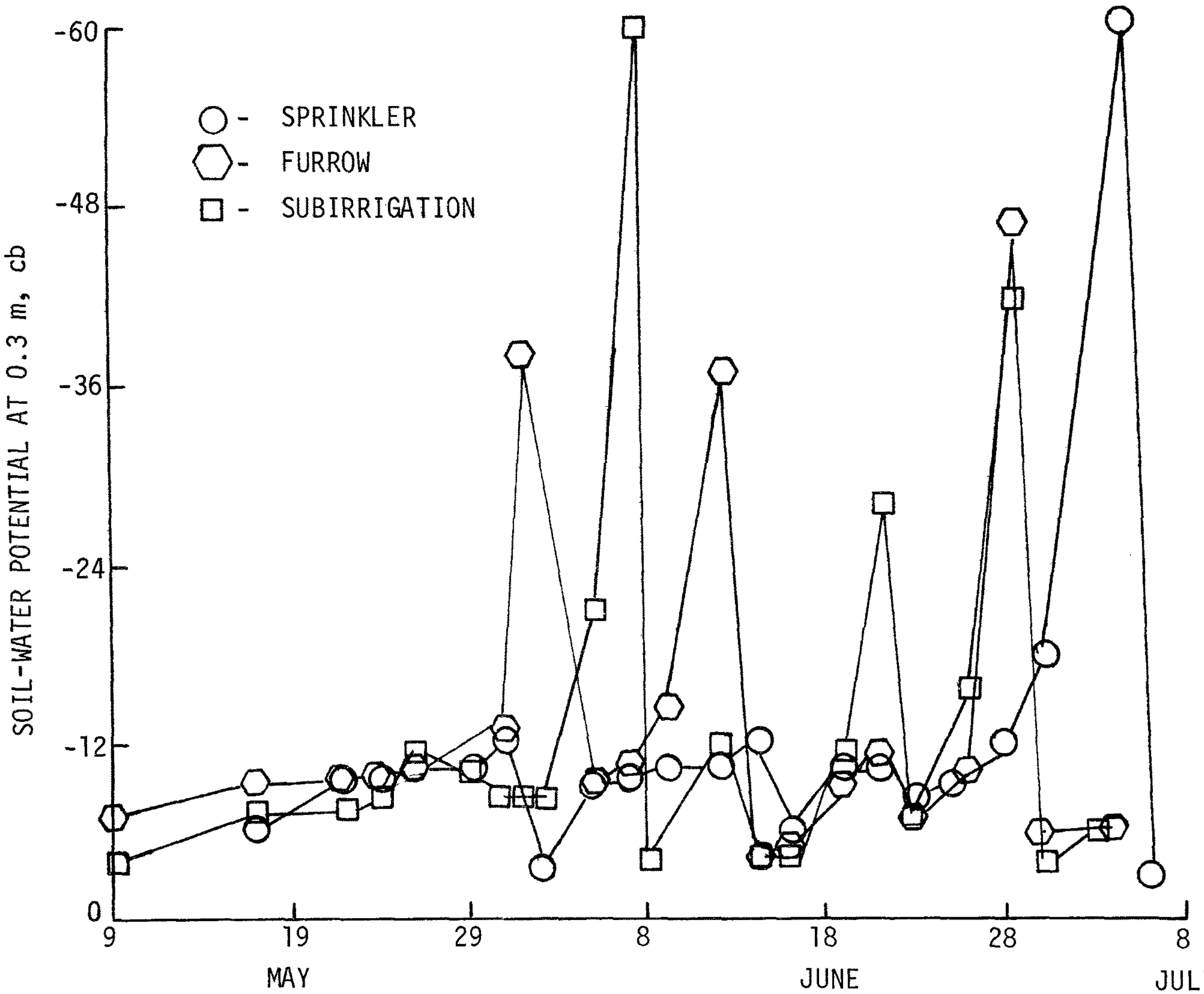


Figure 183. Water potential measured at 0.3 m during the growing season of 1972 for plots fertilized with Uran, planted to sweet corn and irrigated by three methods.

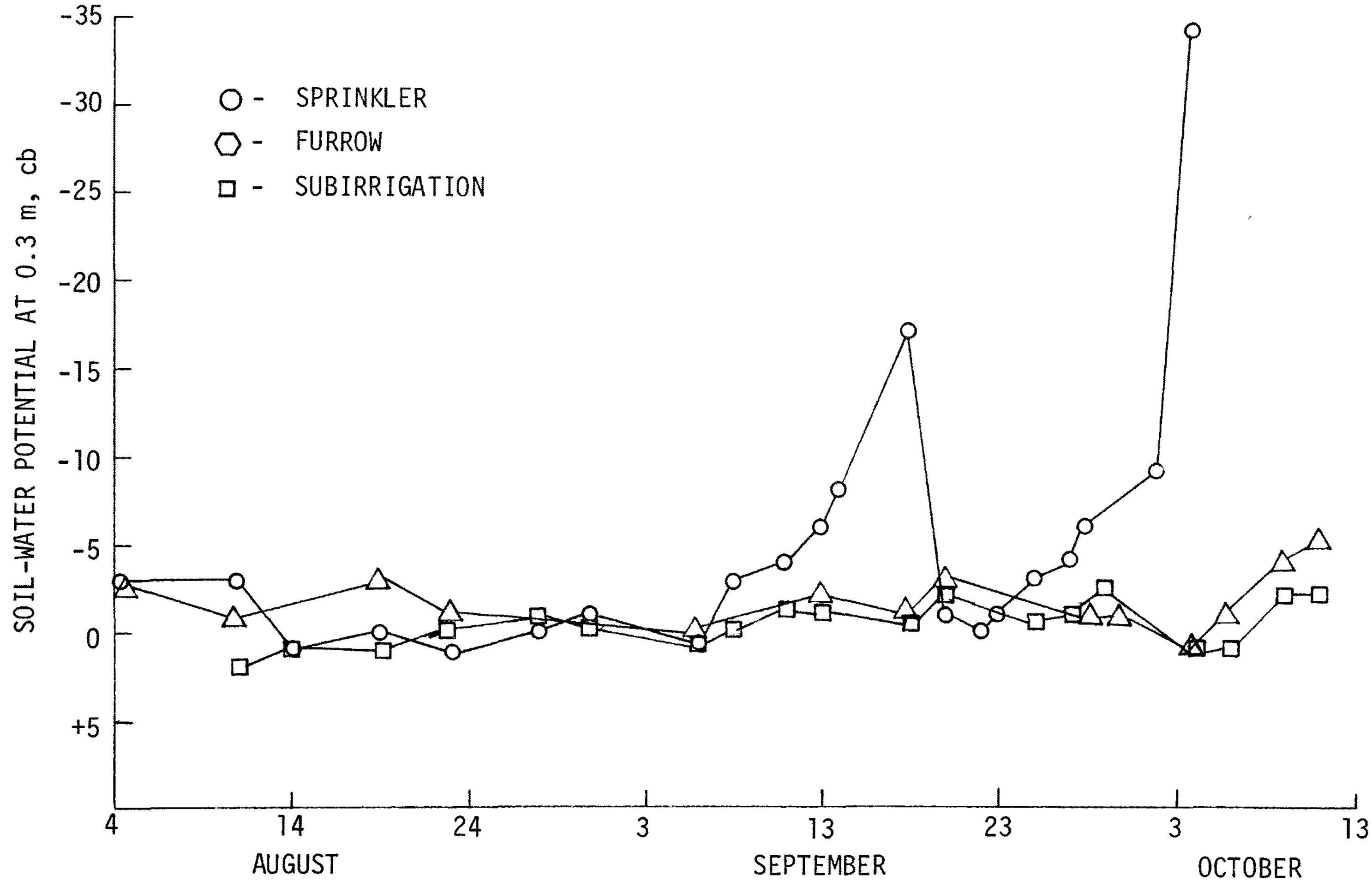


Figure 184. Water potential measured at 0.3 m during the growing season of 1972 for plots fertilized with sodium nitrate and sodium bromide, planted to sweet corn and irrigated by three methods.

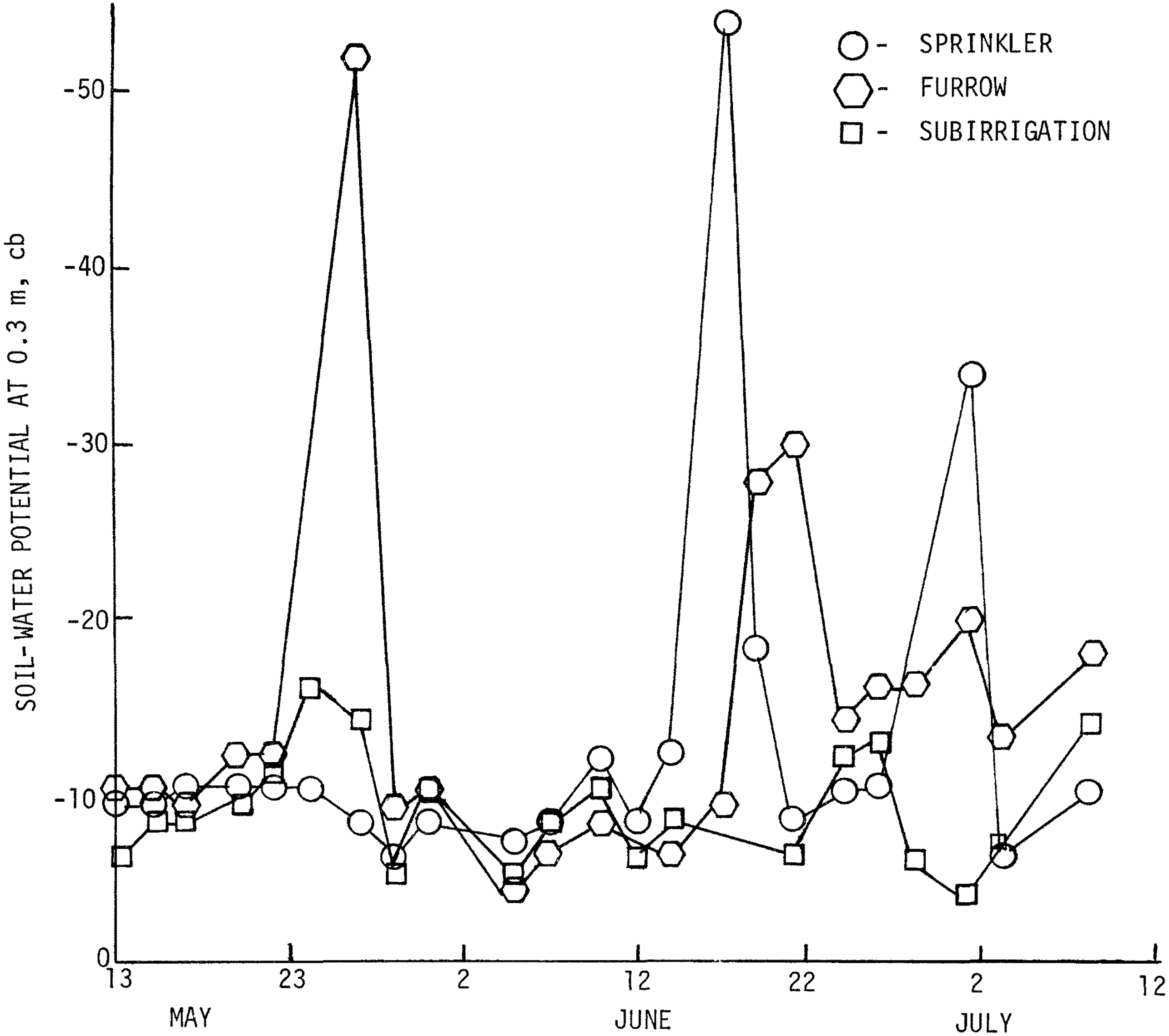


Figure 185. Water potential measured at 0.3 m during the growing season of 1974 for plots fertilized with ^{15}N-enriched sodium nitrate, planted to sweet corn and irrigated by three methods.

denitrification, some of it may also have been tied up in the root system of the crop and was not included in the soil sample analyses. The same statements could be made for the 14% that was not recovered for the furrow plots, and possibly in this situation a somewhat greater amount of fertilizer might have been lost due to denitrification in that, as shown in the tables containing the data for nitrate-N distribution in the profile, nitrate-N was held up in the profile longer in the furrow plots than in the sprinkler plots, thus increasing the potential for denitrification. The recovery of only 50% of the fertilizer nitrogen from the subirrigated plots and the data showing that the nitrogen was not in the plant material nor in the soil profile is strongly indicative of loss through denitrification. Certainly the conditions necessary for denitrification were present; namely, nitrate retention in the upper portions of the soil profile, low water potentials and a readily available energy source for anaerobic organisms, which was apparently used.

In conclusion, the quality of irrigation return flow to underground water was much superior under subirrigation compared to the other two irrigation systems from the standpoint of nitrate-N from applied fertilizer. The reason for this apparently was the retention of nitrate-N that was banded into the soil above the subirrigation lateral, the maintenance of water potentials at or above field capacity for substantial time periods in a zone with the nitrate and in a zone where an energy source was available for the anaerobic organisms to convert the nitrate to a gaseous nitrogen form where it was lost into the atmosphere. Thus, not only can we, through use of this system, have a good quality irrigation return flow, from the standpoint of fertilizer nitrate, by reducing its movement; but it is, in fact, removed from the soil environment altogether if it is not used or incorporated into plant tissue. Whether removed from the soil by the process of denitrification or incorporated in plant tissue, it is not subject to leaching by rainfall during winter months and thus the movement of the nitrate under this system into underground water would certainly be minimized.

Water Requirements of Sweet Corn Irrigated With Furrow, Sprinkler, Manual Subirrigation and Automatic Subirrigation

Investigation of the much-discussed concept of using irrigation water more efficiently to decrease the amount of water available for irrigation return flow and amount of salt applied was one of the objectives of this project. The facilities of this project afforded the opportunity to compare sprinkler irrigation, furrow irrigation, subirrigation, and automatic subirrigation as to their efficiency of water application. Descriptions of these systems are presented in the Methods and Materials Section.

The generalized water budget model used in comparison was:

$$\Delta W = M + Ir - N - F - (E+T) \qquad \text{[Hillel (8)]} \qquad [19]$$

(Definitions on following page)

Parameter			Method of Measurement
ΔW	=	Change in water content	Calibrated neutron probe
M	=	Precipitation	Rain gauge
Ir	=	Irrigation water	Flow meter
N	=	Runoff)	None during the growing season of the crop
F	=	Deep percolation)	
E+T	=	Evaporation + Transpiration or Evapotranspiration (ET)	

During the growing season, there was no runoff from the plots. Also, the location of peak concentrations of a bromide tracer in the root zone remained nearly constant during the growing season. This fact indicates that there was negligible deep percolation during this period. Since there was no runoff or deep percolation from the plots, Equation 19 became the following:

$$ET = M + Ir - \Delta W \qquad [20]$$

Criteria for applying water through the various irrigation systems are shown in Table 41. Water was applied when the potential at 30 cm decreased to -40 cb. Due to the porosity of the loamy fine sand soils, it was not possible to apply less than 7.6 cm of irrigation water per application with the furrow system. In the sprinkler-irrigated and manually-subirrigated plots, it was possible to apply a percentage of potential ET at each application varying according to stage of growth. Water was applied as needed to the automated subirrigated plots when the potential decreased to -40 cb until the potential increased above -40 cb. Eight replications of yield data were obtained from each treatment.

TABLE 41. CRITERIA FOR APPLYING IRRIGATION THROUGH THE VARIOUS SYSTEMS IN A COMPARISON OF THE WATER EFFICIENCY OF IRRIGATION SYSTEMS IN KNOX COUNTY, TEXAS, 1973

System	Indicator	Reading, cb	Amount of water applied
Furrow	Tensiometer	40	7.62 cm
Sprinkler	Tensiometer	40	Percentage of potential ET*
Subirrigation	Tensiometer	40	Percentage of potential ET*
Automatic subirrigation	Switching tensiometer	40	Adequate to increase potential above -40 cb

* Potential ET as proposed by Jensen, et al. (10).

The water applied and yield of the sweet corn in the study are shown in Table 42. On the surface it would appear that possible breakthroughs in the amount of water required by sweet corn might be forthcoming. Essentially, the same yield of sweet corn was obtained when 13.0 cm of water were applied using automatic subirrigation, 20.2 cm using manual subirrigation, 25.1 cm using sprinkler irrigation, and 38.1 cm using furrow irrigation. Similar variation existed among irrigation systems, i.e., some of the subirrigated plots used over 25 cm and some of the sprinkled plots used as low as 20 cm (Table 42). The treatments discussed in this section received the same fertilizer treatments of 45.5 kg of nitrogen in the form of Uran applied through the irrigation water.

Rainfall and irrigation distributions during the studies are also shown in Table 42. In the furrow plot, five 7.62-cm irrigations were applied. Five irrigations varying anywhere from 4.19 to 6.86 cm were applied to the sprinkler-irrigated plot. Three applications of water which varied from 5.33 to 8.00 cm were applied to the manual subirrigation plot. To the plot with automatic subirrigation, 25 applications varying from 0.15 to 0.86 cm/application were applied. In general, the amounts applied through the automated subirrigation system were in the range of the amounts received in showers from rainfall.

Major differences occurred in the soil-water content among treatments in the soil profile (Figures 186 and 187). As shown in Figures 10, 11, and 12, the soil profile is quite variable, but among the systems there were some characteristics in common. In general, with furrow irrigation systems, water was applied in excess of potential ET due to the characteristics of the system such that at the end of the season there was an increase in soil-water content compared to the beginning of the season. In the sprinkler-irrigated treatment, a portion of the soil profile had a water content increase, and a portion of it had a decrease between the beginning and end of the season. Below 3 m, drainage occurred from the winter rains prior to the growing season. In the case of subirrigation, there was a slight decrease in water content in the root zone and a decrease below the root zone indicating drainage during the growing season. Treatments with automatic subirrigation had a major decrease in the soil-water content of the soil profile above 1.8 m during the growing season. Due to major differences in soil-water content changes during the growing season among the systems, the variation in the amount of water used by sweet corn irrigated by the different systems (Figure 188) was much less than the variation in the amounts of water applied (Table 42). Corn irrigated with the furrow system still required the most water--36.1 cm, while the corn irrigated with the sprinkler and subirrigation systems required 34.6 and 34.0 cm, respectively. The corn irrigated with the automated subirrigation system required 30 cm of water or 6.1 cm less than the furrow irrigation system. The accumulative ET based on changes in water content and water applied parallels the potential ET line in the latter part of the growing season, indicating that the crop at this time was using water approximately equal to the potential ET.

Leaf area measurements of the corn growing on the various systems were made using a relationship between plant diameter 2.54 cm above the ground and the leaf area for each different system. In Figure 189, it can be seen

TABLE 42. RAINFALL RECEIVED AND IRRIGATION WATER APPLIED TO SELECTED PLOTS IN THE VARIOUS IRRIGATION SYSTEMS IN KNOX COUNTY, TEXAS, IN 1973

Date	Rainfall, cm	Irrigation water applied, cm			
		Sprinkler	Furrow	Subirrigation	Automated subirrigation
May 13	0.25				
14	0.43				
21	0.25				
22	0.89				
23	0.13				
June 1	2.84				
2	0.48	6.86			
5	0.38				
7					0.43
8			7.62		0.20
11	0.18				0.28
13	0.36			7.24	
14					0.43
15					0.28
16					0.15
17					0.71
18			7.62		0.58
19	0.33	5.72			
20					0.58
21				5.33	0.71
22					0.43
23					0.43
25			7.62		0.15
26					0.86
27		4.19			0.46
29	0.56				0.71
30					0.58
July 2			7.62	8.00	0.71
3		4.32			0.71
4					0.43
5					0.71
7					0.71
8					0.71
9		4.45	7.62		
11	1.27				0.58
12					0.61
Totals	8.35	24.27	38.10	20.57	13.14
Yield, ears/ha		40,138	38,902	43,225	39,520 *

*Yields are not significantly different at the 5% level of probability.

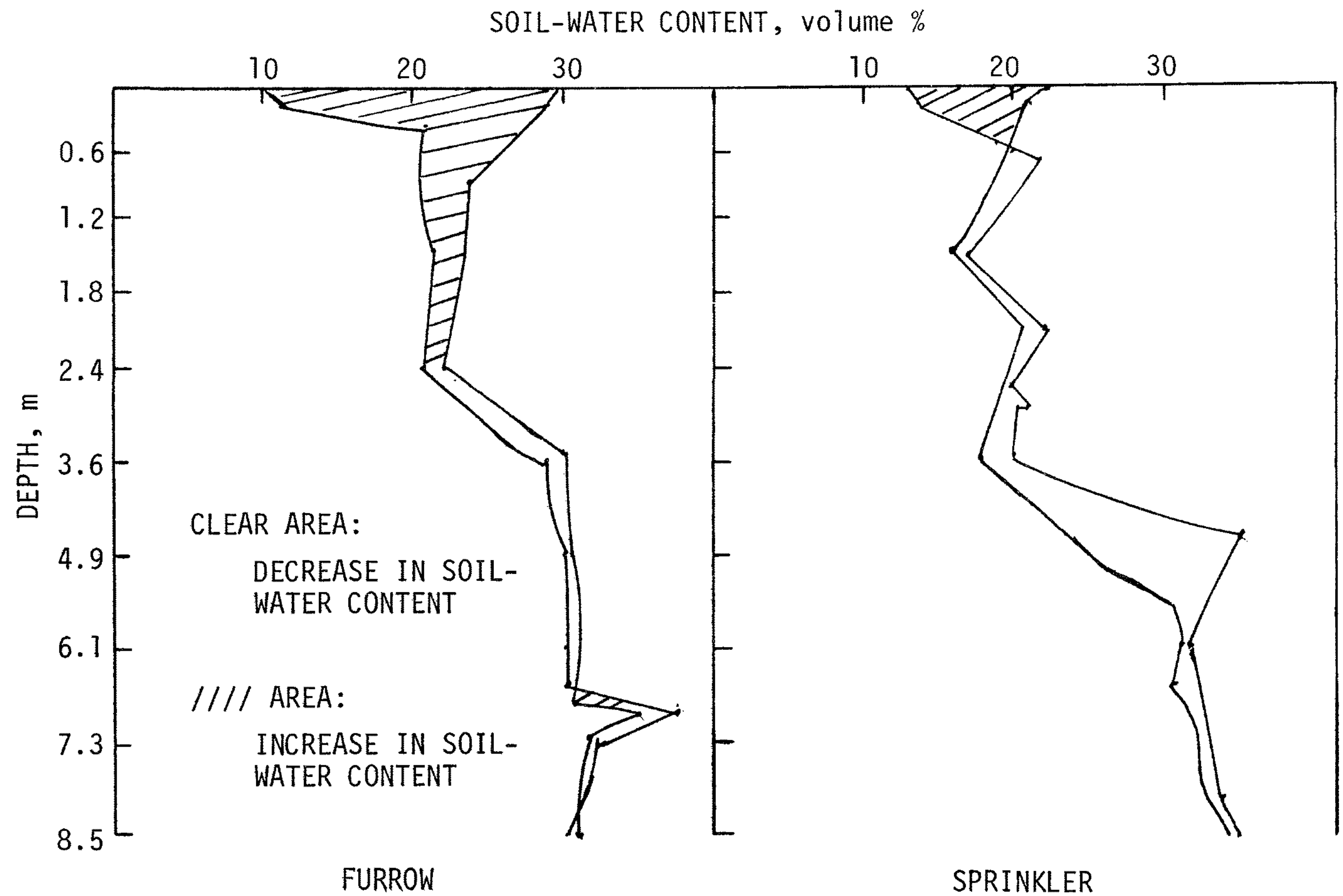


Figure 186. Changes in soil-water content with depth between the beginning and end of the growing season in the furrow- and sprinkler-irrigated plots in the 1973 irrigation systems study, Knox County, Texas.

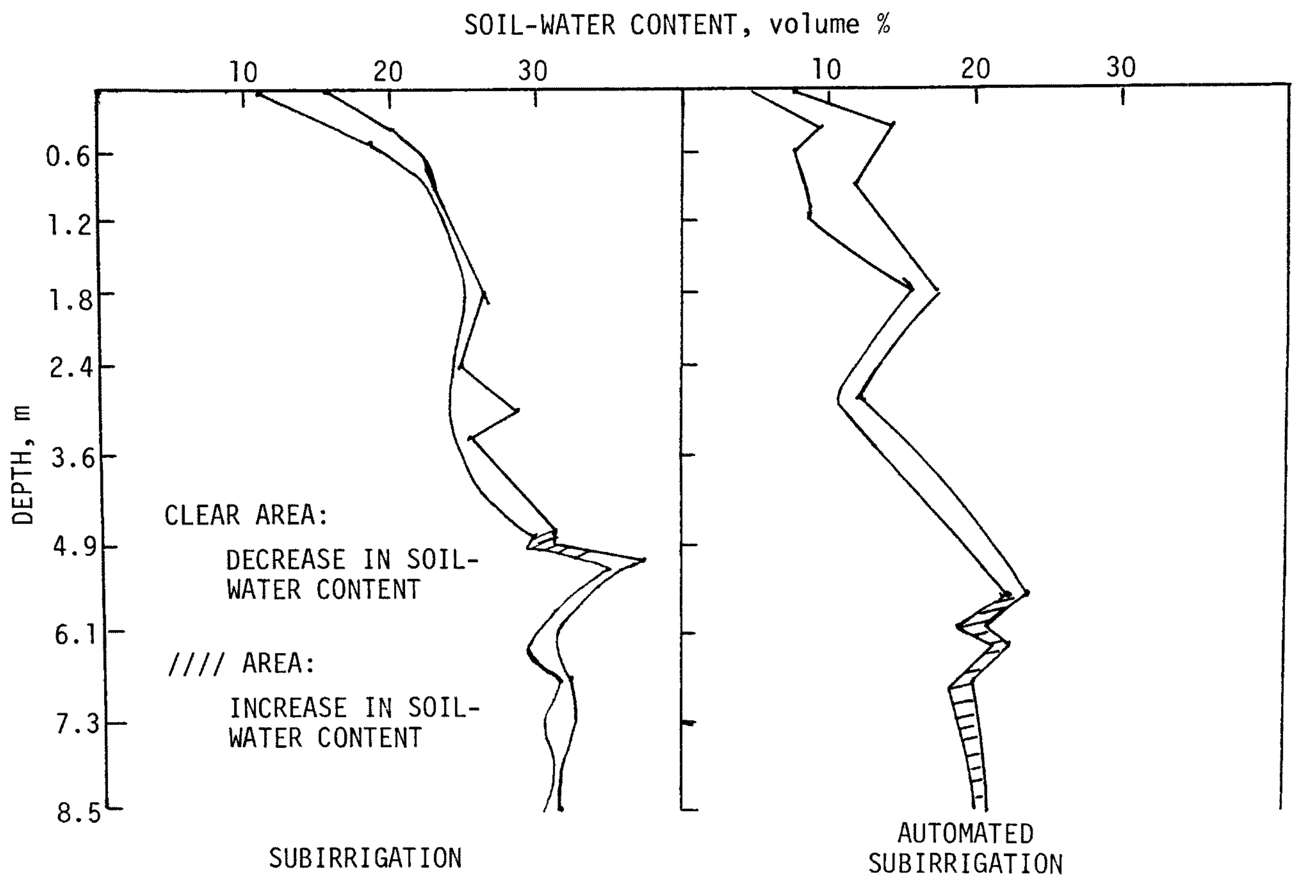


Figure 187. Changes in soil-water content with depth between the beginning and end of the growing season in the manually- and automatically-subirrigated plots in the 1973 irrigation systems study, Knox County, Texas.

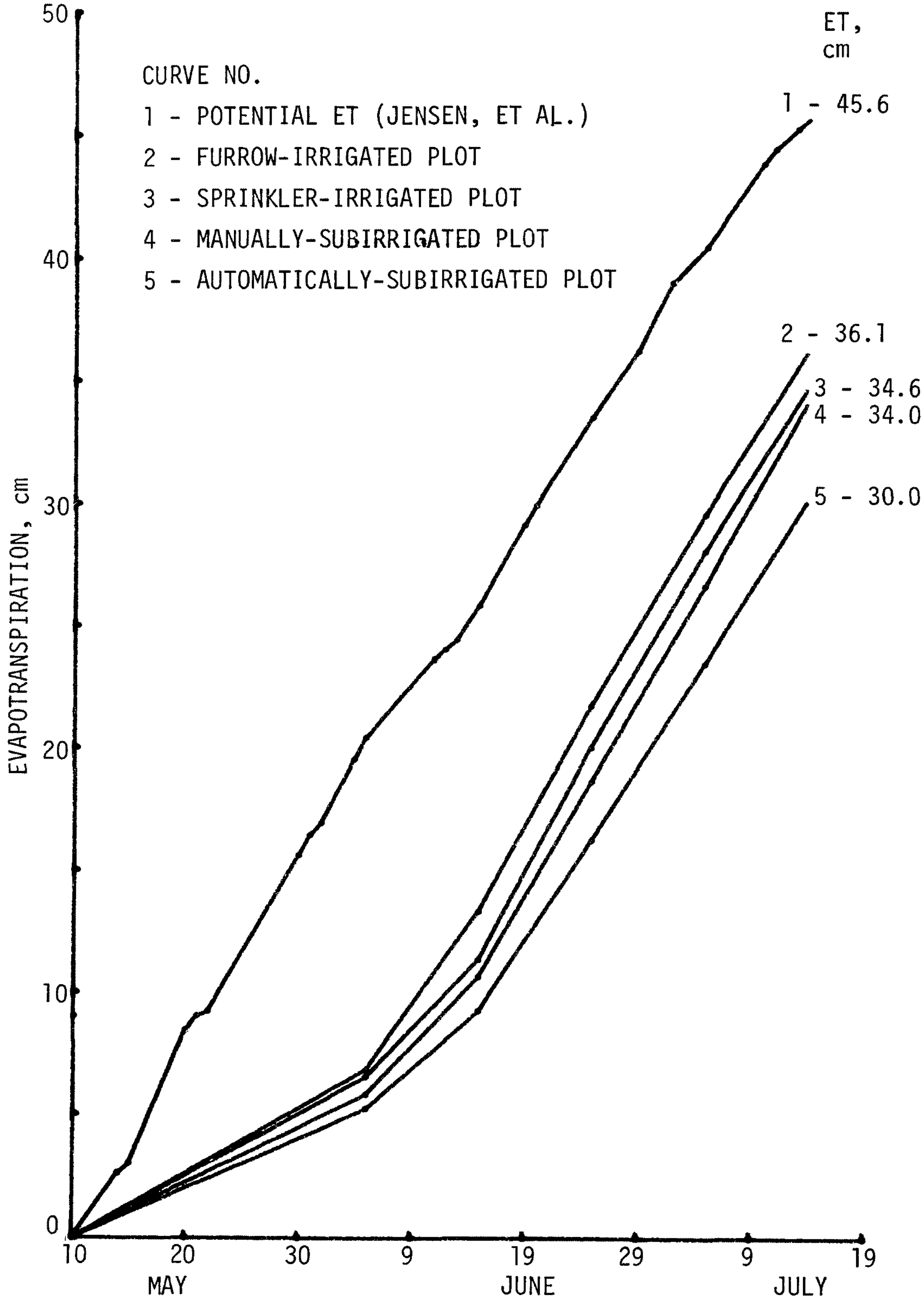


Figure 188. Potential vs measured evapotranspiration of sweet corn irrigated with various irrigation systems in Knox County, Texas, 1973.

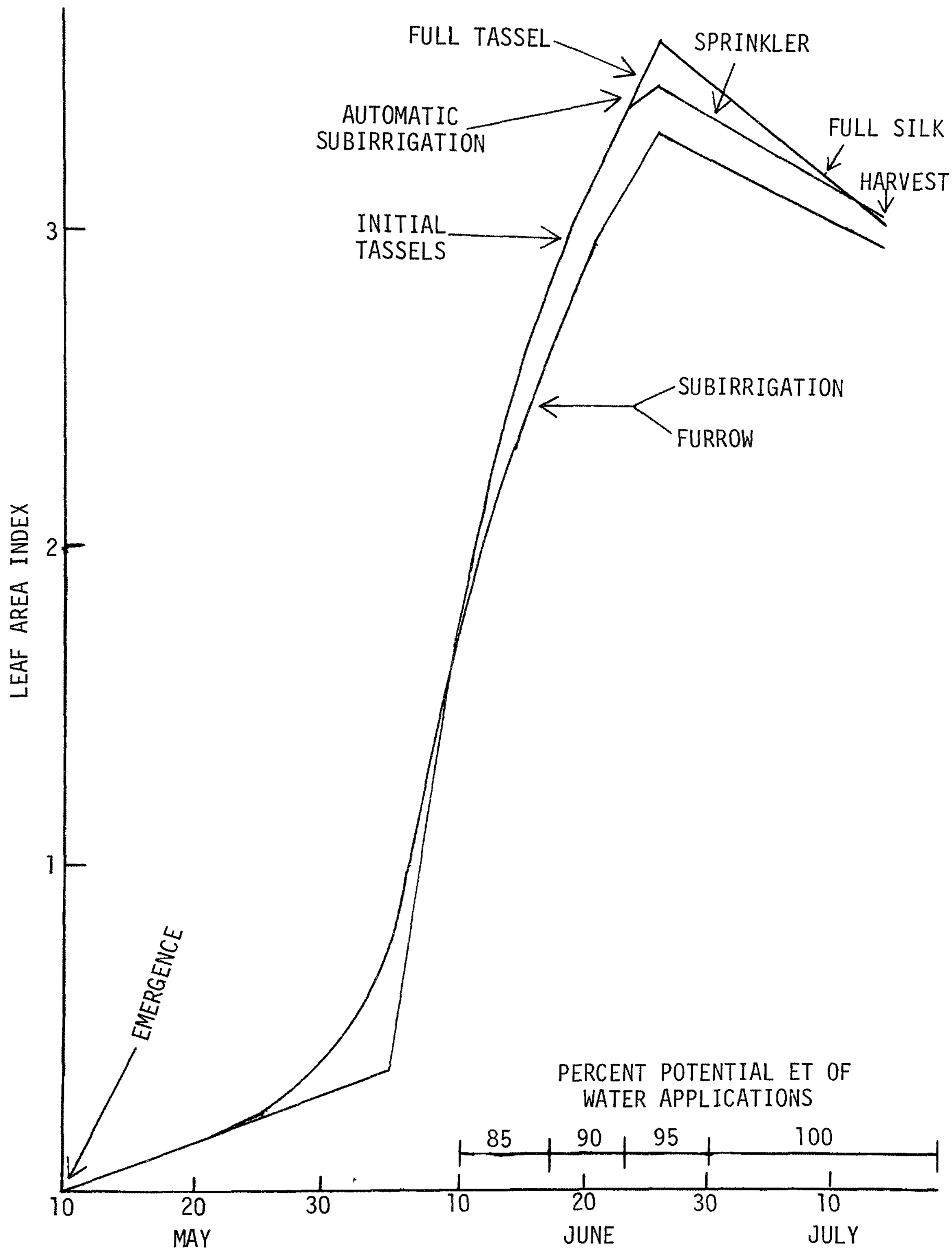


Figure 189. Leaf area index of sweet corn produced with various irrigation systems, Knox County, Texas, 1973.

that there was little difference in the LAI of corn grown over the furrow irrigation and the manual subirrigation systems. The corn grown with the automatic subirrigation and sprinkler irrigation systems was slightly greater in leaf area.

Plant evaporation in relation to potential evaporation as influenced by leaf area was compared to a relationship derived by Ritchie and Burnett (21) (Figure 190). It can be seen that the points for subirrigation fall slightly below the line, whereas most of the other points are above the line. This indicates that the corn grown on the different irrigation systems followed this particular relationship. This would also indicate that, although there were different amounts of water applied to the crop, no major breakthroughs relative to water requirements of crops were obtained -- but rather major increases in water application efficiency due to differences in irrigation systems.

In conclusion, when one considers the changes in water content along with irrigation water applications, there was little difference in ET by sweet corn grown over the different systems. Therefore, what on the surface may appear to be a major breakthrough in water requirements of crops can be explained by decreases in soil-water content. It appears from these data that a sweet corn crop required approximately the same amount of water for a given yield regardless of the irrigation system. However, automation of irrigation systems does afford the possibility of making more efficient use of water stored in soil profiles. This factor should not be discounted in those areas where supplemental irrigation rather than full irrigation is used. A zone of lower moisture content can be developed to store rainfall yet the crop can obtain adequate moisture and not become stressed. It is realized that sophisticated irrigation systems do not exist except on high value crops. However, it is believed that automation of furrow and sprinkler systems deserves further investigation as a means of increasing application efficiency. Irrigation return flow can be reduced in those areas that do not require a leaching requirement by either automated system or by use of a measure of ET as a basis of irrigation. However, in most irrigated areas, leaching requirements would need to be included and such a requirement could be built into automated systems or included along with the ET potential.

It should be pointed out that, in these treatments, no applied water or nutrients moved below the root zone during the growing season from any of the treatments. Although more water was applied with the manually-operated system, the use of potential ET as a basis for scheduling applications could also be used to minimize water available for irrigation return flow. Such a scheduling technique could also include the leaching requirement.

OBJECTIVE 4 - ECONOMICS OF INSTALLATION, OPERATION, AND MAINTENANCE OF SUBIRRIGATION SYSTEMS AND OF EACH FERTILIZATION PRACTICE

Economic Implications of Sprinkler Irrigation, Furrow Irrigation, and Subirrigation Systems Fertilized With Various Rates of Nitrogen

Based on the results obtained from 1971-1973, some general economic implications emerge. Since estimated costs and returns for the alternative

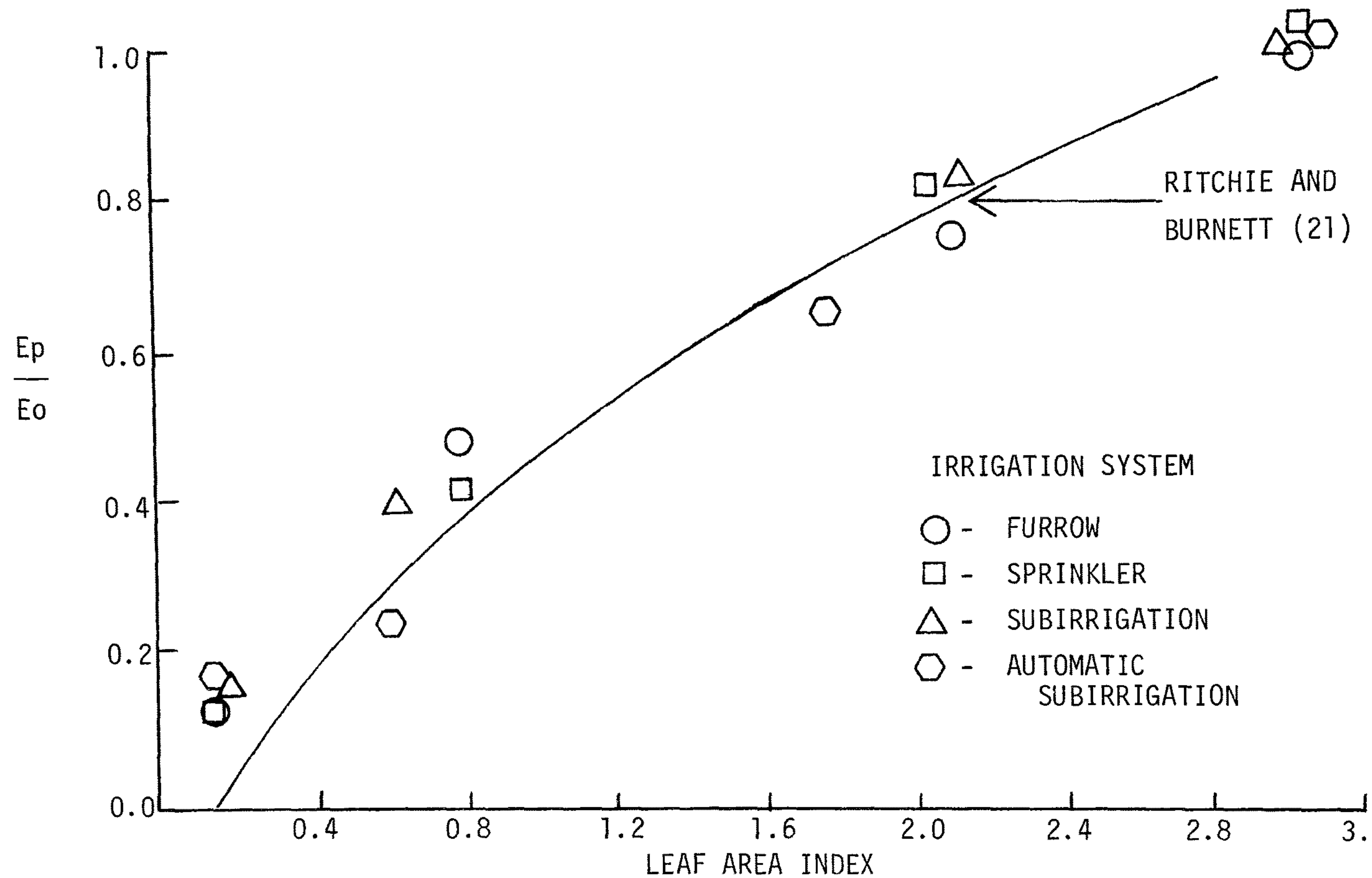


Figure 190. Plant evaporation (Ep) of sweet corn produced with different irrigation systems in relation to potential evaporation (Eo) as influenced by leaf area index.

irrigation distribution systems are closely related to crop yield, the per hectare yield for each year (1971-1973) is presented for reference in Table 43, by research plot. Per hectare yields were based on ear weight in each plot. Water and fertilizer applied for each situation shown in Table 43 are indicated elsewhere in the general report.

To maintain consistency, the same price and cost assumptions were applied to each year to estimate per hectare net returns. These input and product prices as well as other input requirements and associated costs were taken from several references (6,12,13,14,22). Basically, costs and returns were calculated using the following data:

Item	Unit	Price or cost, dollars
Returns		
Sweet corn	quintal	$ 15.90
Costs		
General production	hectare	118.90
Labor	hour	2.00
Harvesting	quintal	7.16
Nitrogen	kilogram	0.26
Pumping	ha-cm	1.13

In addition, an annual fixed cost, based on investment, was included for each irrigation distribution system ($6.72 - furrow, $19.96 - sprinkler, $300.52 - manual subirrigation, and $374.45 - automated subirrigation). The per hectare net returns, by plot and year as shown in Table 43, were estimated based on this information.

With a reduction in the investment required for a subirrigation system ($2,470 per hectare used in this study), annual fixed costs would decline and present a more favorable net return picture. Likewise, a higher sweet corn price would result in higher net returns. Therefore, it is important to be aware of the limitations of the assumed prices and costs used for this analysis.

The data in Table 43 were aggregated by year and nitrogen application rate for each of the distribution systems. In those cases where the nitrogen rate was changed appreciably, the research plot was not included in the aggregation. The research plots included in each aggregation are as follows:

TABLE 43. PER HECTARE YIELD AND EXPECTED NET RETURNS FOR SWEET CORN BY RESEARCH PLOT: 1971-73.

Plot	Yield			Net returns		
	1971	1972	1973	1971	1972	1973
	quintal			dollar		
1	15.8	15.0	34.8	-54.3	-54.3	108.7
2	14.7	21.7	63.1	-81.5	-4.9	321.1
3	22.4	26.4	75.0	-27.2	0	415.0
4	34.2	23.1	80.0	29.6	-29.6	449.5
5	39.1	19.3	69.2	106.2	-59.3	360.6
6	17.5	13.1	62.8	0	-71.6	303.8
7	26.8	19.6	69.2	-17.3	-24.7	373.0
8	41.1	25.0	83.3	113.6	-2.5	476.7
9	19.7	10.8	77.1	-96.3	-130.9	424.8
10	30.9	35.3	79.0	24.7	81.5	439.7
11	10.0	13.4	35.8	-108.7	-69.2	113.6
12	36.0	43.9	75.0	86.5	145.7	407.6
13	52.5	42.6	75.0	232.2	135.9	405.1
14	9.1	11.5	17.9	-116.1	-69.2	29.6
15	39.2	33.3	52.8	150.7	106.2	242.1
16	24.0	81.2	66.4	-7.4	471.8	340.9
17	43.0	53.2	71.7	170.4	239.6	392.7
18	16.4	17.6	70.7	-42.0	-9.9	375.4
19	39.1	27.4	61.0	113.6	46.9	311.2
20	25.1	71.5	50.8	-4.9	390.3	247.0
21	15.1	40.2	66.4	-108.7	128.4	340.9
22	9.4	11.1	16.0	-93.9	79.0	-39.5
23	20.2	46.9	65.4	-29.6	190.2	340.9
24	19.5	32.8	53.3	-34.6	71.6	237.1
25	39.8	43.1	63.5	140.8	158.1	321.1
26	19.9	24.0	70.2	-32.1	-2.5	395.2
27	20.9	17.2	18.9	-289.0	-306.3	-293.9
28	32.9	37.3	54.2	-190.2	-140.8	-17.3
29	43.0	41.3	82.8	-128.4	-145.7	202.5
30	33.7	45.6	71.7	-214.9	-111.2	113.6
31	40.9	63.8	68.8	-148.2	37.1	86.5
32	30.5	20.5	73.1	-210.0	-281.6	121.0
33	58.0	23.5	67.9	12.4	-269.2	88.9
34	40.3	25.8	71.7	-165.5	-271.7	108.7
35	41.4	47.6	58.6	-168.0	-98.8	0
36	45.0	28.6	67.3	-138.3	-261.8	69.2
37	22.3	10.0	24.8	-298.9	-373.0	-251.9
38	40.9	19.7	63.5	-160.6	-335.9	39.5
39	42.4	42.1	41.2	-145.7	-145.7	-148.2

Continued

TABLE 43. (Continued)

Plot	Yield 1971	Yield 1972	Yield 1973	Net returns 1971	Net returns 1972	Net returns 1973
	quintal			dollar		
40		24.8	50.8		-343.3	-123.5
41		27.0	62.0		-321.1	-17.3
42		19.0	30.5		-353.2	-266.8
43		33.0	52.8		-266.8	-108.7
44		34.2	69.8		-256.9	-49.4
45		18.4	29.6		-358.2	-269.2
46		36.2	43.1		-24.7	49.4

System	Nitrogen rate, kg/ha	Research plots
Sprinkler	0	1, 11
	22.4 - 67.2	2, 7
	112.0	3-5, 8-10, 12, 13
Furrow	0	14, 22
	22.4 - 67.2	15, 19
	112.0	16, 17, 20, 21, 23-26
Manual Subirrigation	0	27, 37
	22.4 - 67.2	28, 33
	112.0	29-31, 34-36, 38, 39
Automated Subirrigation	0	42, 45
	112.0	40, 41, 43, 44
Trickle	112.0	46

The aggregated results for yield per hectare and expected net returns are presented in Table 44. For each nitrogen application rate and distribution system, the 1973 yield per hectare was appreciably larger than 1971 and/or 1972. This increased yield is generally reflected in the corresponding expected net returns. Therefore, it is appropriate to first consider the 1973 results.

Yields in 1973 associated with the manually-operated subirrigation system were a) less than that indicated using sprinkler irrigation and b) about the same or a little larger than yields obtained with furrow irrigation, for each fertilization rate. Net returns per hectare, by fertilization rate, were significantly lower using the subirrigation systems compared to sprinkler or furrow irrigation. Over the three-year period

TABLE 44. PER HECTARE YIELD AND EXPECTED NET RETURNS FOR SWEET CORN FOR ALTERNATIVE FERTILIZER RATES AND METHODS OF APPLYING IRRIGATION WATER, 1971-1973

System	Nitrogen	Yield				Net returns			
		1971	1972	1973	Avg.	1971	1972	1973	Avg.
		quintal				dollar			
Sprinkler	0	12.9	14.2	35.4	20.8	-81.51	-61.75	111.15	-10.70
	22.4 - 67.2	20.7	20.6	66.2	35.6	-49.40	-14.82	345.80	93.86
	112.0	34.5	28.3	76.6	46.5	59.28	17.29	422.37	166.31
Furrow	0	9.3	11.3	17.0	12.5	-103.74	4.94	-4.94	-34.58
	22.4 - 67.2	39.2	30.4	56.9	42.1	130.91	76.57	276.64	161.37
	112.0	25.9	49.2	63.5	46.1	9.88	205.01	326.04	180.31
Manual subirrigation	0	21.6	13.7	21.8	19.0	-293.93	-340.86	-271.70	-302.16
	22.4 - 67.2	45.5	30.5	61.0	45.7	-88.92	-205.01	37.05	-85.63
	112.0	41.0	39.3	65.7	48.7	-158.08	-165.49	59.28	-88.10
Automated subirrigation	0		18.7	30.0	24.4		-355.68	-269.23	-312.46
	112.0		29.7	58.8	44.2		-296.40	-49.40	-172.90
Trickle	112.0		36.2	43.1	39.6		-24.70	49.40	12.35

(1971-1973), net returns were positive for subirrigation in 1973 only; i.e., $37 for 22.4 to 67.2 kg of nitrogen and $59 for 112 kg of nitrogen.

The three years' data were averaged to determine expected yields and net returns for the alternative situations. The first year (1971) was one of testing and gaining experience with the equipment while 1973 was a year of exceptionally good growing conditions. Considering the manually-operated subirrigation system, associated yields at each fertilization level were larger than sprinkler or furrow irrigation with the single exception of no nitrogen fertilizer and sprinkler irrigation. With 112.0 kg of nitrogen fertilizer, average yield with the subirrigation system was 48.7 quintal compared to about 46.4 quintal with sprinkler and furrow irrigation.

Even with the increased yields, the larger fixed costs of subirrigation due to the $2,470/ha initial investment more than offset any yield advantage. Net returns were negative for all situations using subirrigation (-$302, -$86, and -$88 for 0, 22.4 to 67.2, and 112 kg of nitrogen, respectively). Net returns for 112 kg of nitrogen were about $173/ha for the sprinkler and furrow irrigation systems or over $240 greater than with subirrigation.

The net return estimates indicate that the assumed investment in subirrigation systems of $2,470/ha cannot be economically justified. However, subirrigation technology could quickly reduce investment costs as well as further increase yields, relative to traditional irrigation systems. Therefore, the analysis was extended to a) establish the investment in a subirridation system which would produce the same net returns per hectare as sprinkler and furrow irrigation given average yields of Table 44, and b) establish the yield required to produce the same net returns per hectare as sprinkler and furrow irrigation given the $2,470/ha manual subirrigation investment and $2,780/ha automated subirrigation investment.

Break-even investment for a subirrigation system is shown in Table 45. For example, with 112 kg of nitrogen applied, an investment of $528/ha in a subirrigation system would result in the same net returns as a sprinkler irrigation system. This indicates that if the investment was lower than $528/ha, the subirrigation system would be more profitable than a sprinkler system.

For 112 kg of nitrogen applied to sweet corn, the break-even investment for a manual subirrigation system is $528 when compared to a sprinkler system and $407 compared to a furrow system. With nitrogen reduced to 22.4 to 67.2 kg/ha, a much larger break-even investment evolves; i.e., $1,126 analyzed against furrow.

Break-even investment for the automated subirrigation system, with 112 kg of nitrogen applied, indicates a smaller value than for the manual system which means it is at a comparative disadvantage. Comparing an automated system to a sprinkler system, the investment in the automated system must be held down to about $432/ha for production to be as profitable as with a sprinkler system. The investment could be only $311 to be comparable to furrow irrigation net returns.

TABLE 45. ESTIMATED PER HECTARE SUBIRRIGATION INVESTMENT WHERE NET RETURNS WOULD BE EQUAL TO NET RETURNS FOR SPRINKLER AND FURROW IRRIGATION BASED ON 1971-1973 DATA*

Nitrogen applied	Manual subirrigation		Automated subirrigation	
	Sprinkler	Furrow	Sprinkler	Furrow
—— kg ——	—————— dollars ——————			
0	133	336	1,971	2,174
22.4 - 67.2	1,126	580	†	†
112.0	528	407	432	311

*Based on average yields and operation costs, by system, for 1971-1973.
†Information not available.

This suggests the manual subirrigation system is closer than the automated system to being economically feasible. These data indicate that the investment in a subirrigation system will have to decline to about $500 to $750/ha before they are economically competitive with traditional systems.

Viewing break-even yield, Table 46 shows the estimated yield under subirrigation where net returns with subirrigation would be equal to sprinkler and furrow irrigation, given an investment of $2,470 and $2,780/ha for a manual and automated system, respectively. Considering only situations with nitrogen fertilization, the break-even yields for both subirrigation systems compared to sprinkler and furrow irrigation are relatively close. For 112 kg of nitrogen, the break-even yields are 63.8 to 66.1 quintal/ha across all systems. This represents a one-third increase in 1971-1973 average yield for the manual subirrigation system and a 50% yield increase for the automated subirrigation system.

Among the many limitations of this economic analysis are a) no consideration of efficiency of water use which would be extremely important in areas with an exhaustible water supply, b) constantly shifting prices for inputs and products, c) only one crop being included, and d) no marketing problems were considered, etc.

Effect of Irrigation Systems, Irrigation Criteria, and Fertilizer Source on Water-Use and Fertilizer Efficiency

The section on economic evaluation was concerned primarily with systems cost and nitrogen cost and did not deal specifically with the effects of irrigation systems, irrigation criteria, and sources of fertilizer on water-use and fertilizer efficiency. Due to the high interest concerning the efficiency of irrigation systems and sources of fertilizer, it was decided that a discussion of these parameters in more detail would be advisable. The discussion of the influence of the criteria for irrigation water, irrigation system, and fertilizer source on the various yield parameters follows.

TABLE 46. ESTIMATED PER HECTARE SUBIRRIGATION SWEET CORN YIELD WHERE NET RETURNS WOULD BE EQUAL TO NET RETURNS FOR SPRINKLER AND FURROW IRRIGATION BASED ON 1971-1973 DATA*

Nitrogen applied	Manual subirrigation		Automated subirrigation	
	Sprinkler	Furrow	Sprinkler	Furrow
— kg —	quintal			
0	38.1 (99%)‡	38.1 (99%)‡	33.6 (37%)‡	31.4 (30%)‡
22.4 - 67.2	56.0 (24%)‡	60.5 (33%)‡	†	†
112.0	63.8 (32%)‡	65.0 (34%)	66.1 (48%)	66.1 (50%)‡

*Based on average operating costs for 1971-1973 and a subirrigation investment of $2,470/ha for a manual system and $2,790/ha for an automated system.
†Information not available.
‡Percent indicates the percentage increase in yield under subirrigation, compared to Table 45 data, needed to equal yields presented in this table.

Total Yield Per Hectare--

Figure 191 shows the influence of the various criteria used as a basis for applying irrigation water on the yield of sweet corn from the various irrigation systems. In using the growth criteria, water was applied when the first visual stress occurred. In the other treatments, water was applied when a) the soil-water potential reached -20 to -30 cb and b) -40 to -60 cb. It can be seen that the average yield increased approximately 2,000 ears/ha where tensiometers rather than growth was used as the criteria for applying irrigation water. However, furrow irrigation system yields were highest when growth rather than tensiometers were used as the criteria for applying irrigation water. Yields from plots of sprinkler and subirrigation systems were superior when tensiometers rather than growth were used as the criteria for applying irrigation water. Growth was not a criteria for applying water to the automated subirrigation and trickle irrigation systems. The yields from these systems were lower and little difference existed in tension levels. These data suggest that more information is needed relative to obtaining maximum yields from automated systems. No break-throughs in yield were obtained with automated systems. In fact, the yields from non-automated systems were, in general, superior to those from automated systems. It should be borne in mind that these data are a summary of all treatments over four years and that, in many cases, the yields of automated systems were equal to those from non-automated systems.

The influence of the various fertilizer sources on the yield of sweet corn from the various systems is shown in Figure 192. In general, the yield of plots where the fertilizer was applied in the bed was superior to plots where the fertilizer was applied in the irrigation water or in the furrow. Yields of plots where ammonia was applied in the bed were higher than where ammonia + N-Serve was applied in the bed. Yields from the various irrigation systems were normally distributed around the mean of the yields with a few exceptions. Yields where Uran was applied in the furrow in the furrow-irrigated plots were superior to those from the subirrigated plots. Also,

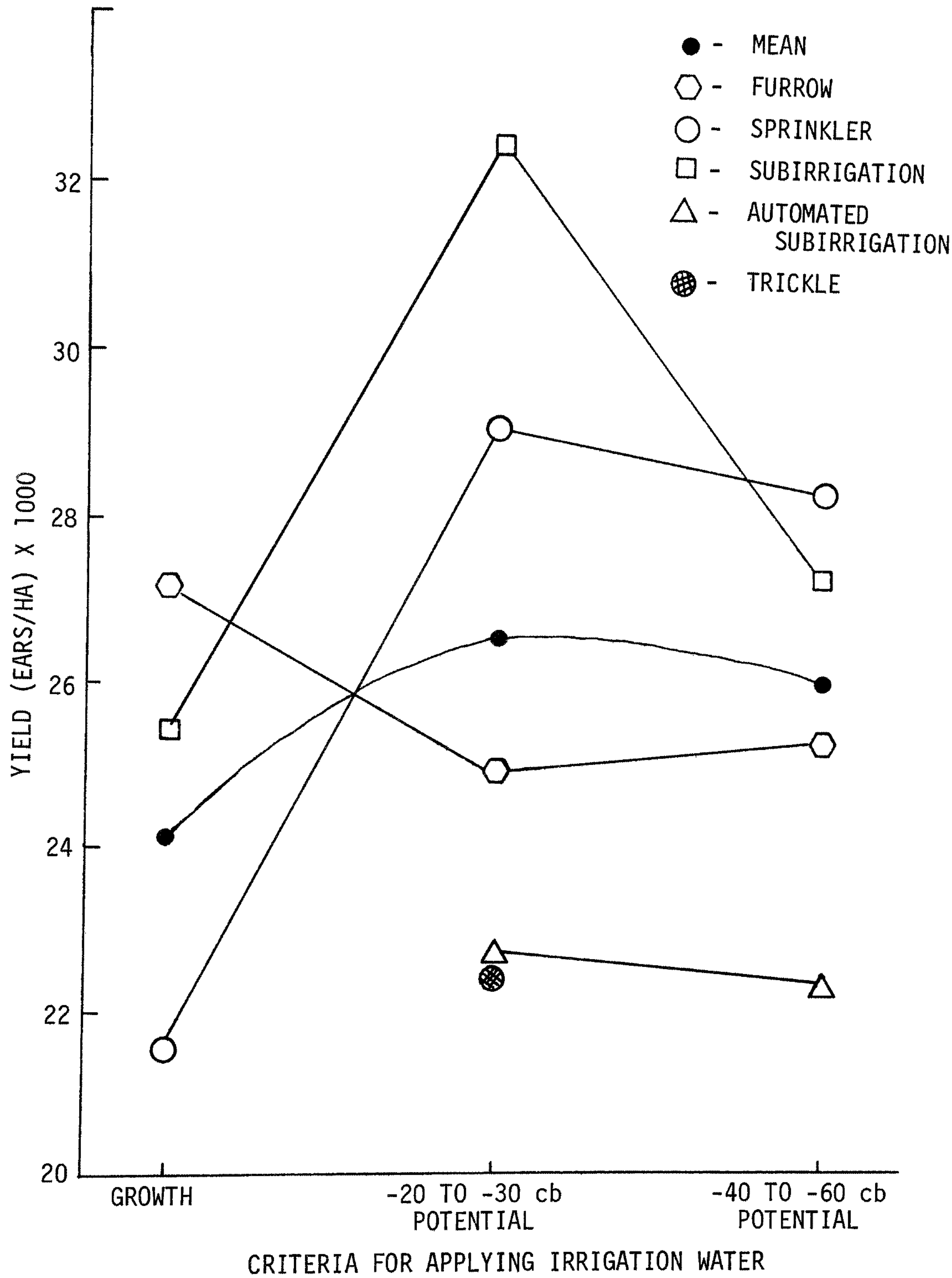


Figure 191. Yield of sweet corn of different irrigation systems as influenced by different irrigation criteria, 1971-1974, Knox County, Texas.

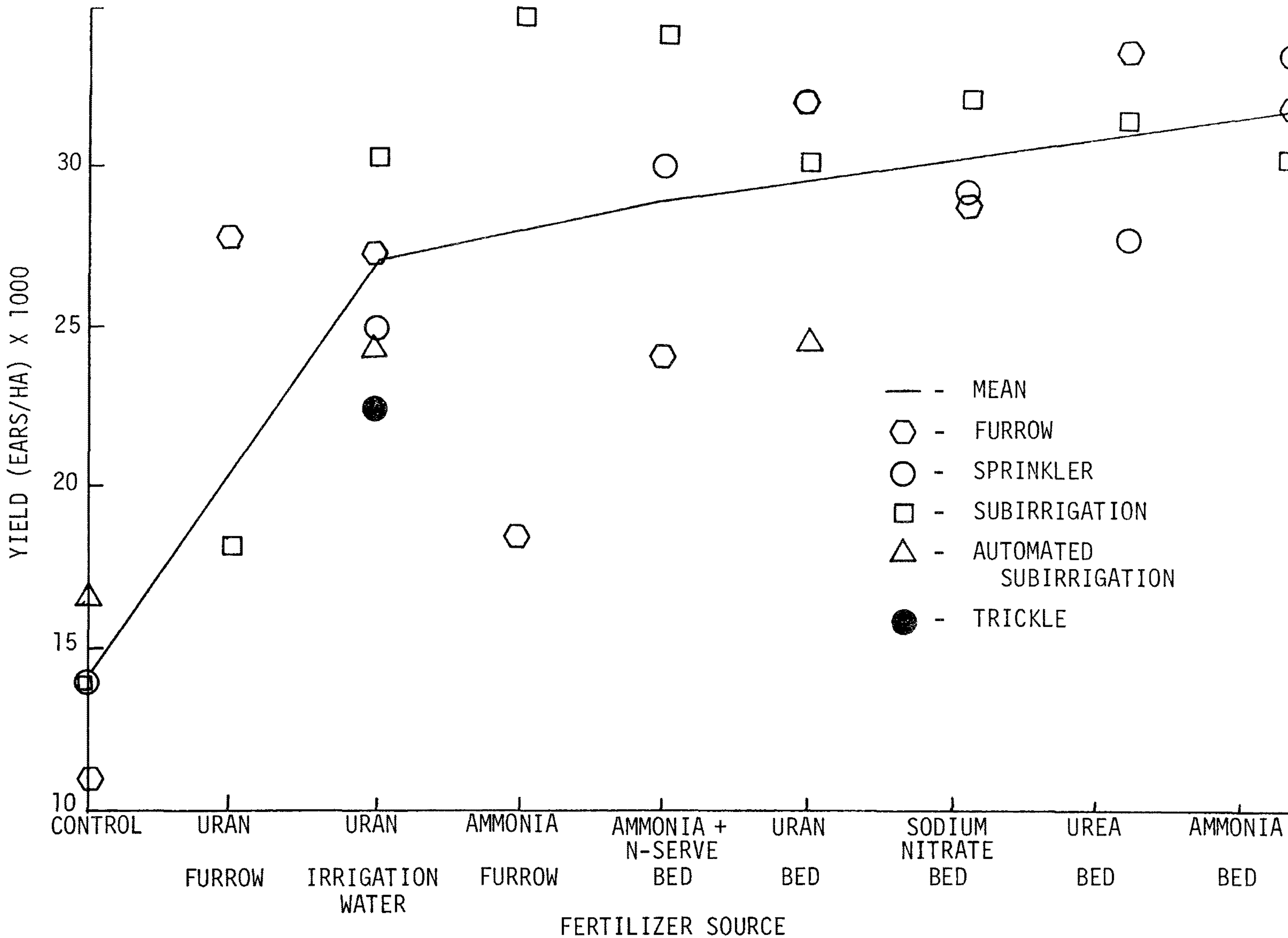


Figure 192. Yield of sweet corn from different irrigation systems as influenced by fertilizer source and method of application, 1971-74, Knox County, Texas.

yields of treatments of the subirrigated plots where ammonia was applied in the furrow and in the bed with N-Serve were superior to those from the furrow-irrigated plots.

In summary, there appears to be some advantage in irrigating on the basis of soil-water potential rather than stage of growth of the crop. Yields tended to be better, with the exception of the automated plots, in most cases where the fertilizer was applied in the bed rather than the furrow or irrigation water. No major differences existed between fertilizer sources when the sources were applied in the bed.

Yield Per Unit of Water--

There was little difference in the mean yield per cm of water of the different irrigation criteria (Figure 193). The yields of the subirrigated plots were greater than the mean yield where the yields from the automated trickle plot were approximately equal to the mean. Yields of the furrow- and sprinkler-irrigated plots were less than the mean except for the stage of growth criteria in the sprinkler plot system and the -40 to -60 cb treatment in the furrow-irrigated plot system. These data show that water can be more efficiently used if applied in subirrigation systems than through sprinkler and furrow irrigation systems.

If only the manual subirrigation systems are considered, there is little difference in the mean yield per unit among fertilizer sources and methods of applications with the exception of where the Uran was applied in the furrow (Figure 194). Yields of the different irrigation systems were closely distributed around the mean except in those treatments where ammonia + N-Serve and ammonia were applied in the bed and Uran was applied in the irrigation water. In these treatments, yields (1,600 ears/cm/ha) of the subirrigation system were superior to those of the sprinkler and furrow irrigation systems.

Yields/cm of water from the automated subirrigation systems were far superior to those from other irrigation systems. In summary, yields/cm/ha from the subirrigated plots were superior to the sprinkler- and furrow-irrigated plots. Yields/cm/ha for the subirrigation systems with ammonia + N-Serve applied in the bed, ammonia applied in the furrow, and Uran applied in the water of the subirrigated plots were superior to similar treatments of the furrow- and sprinkler-irrigated plots. The highest yields/cm/ha were obtained when water was applied through automated subirrigation systems and the crop was fertilized with Uran. Due to the major increase in irrigation efficiency with automated systems, it appears that an investigation of the potential of automating other irrigation systems would be worthwhile.

Yield Per Unit of Fertilizer--

The influence of the different criteria for applying irrigation water on the yield per unit of nitrogen was erratic (Figure 195). Where growth was used as the criteria for applying irrigation water, yields/unit of fertilizer from the subirrigation systems were superior to those from the furrow and sprinkler systems. The differences between systems were not large at -20 to -30 cb potential. At -40 to -60 cb, the yield per unit of nitrogen was greatest from the sprinkler plots, intermediate from the subirrigated and

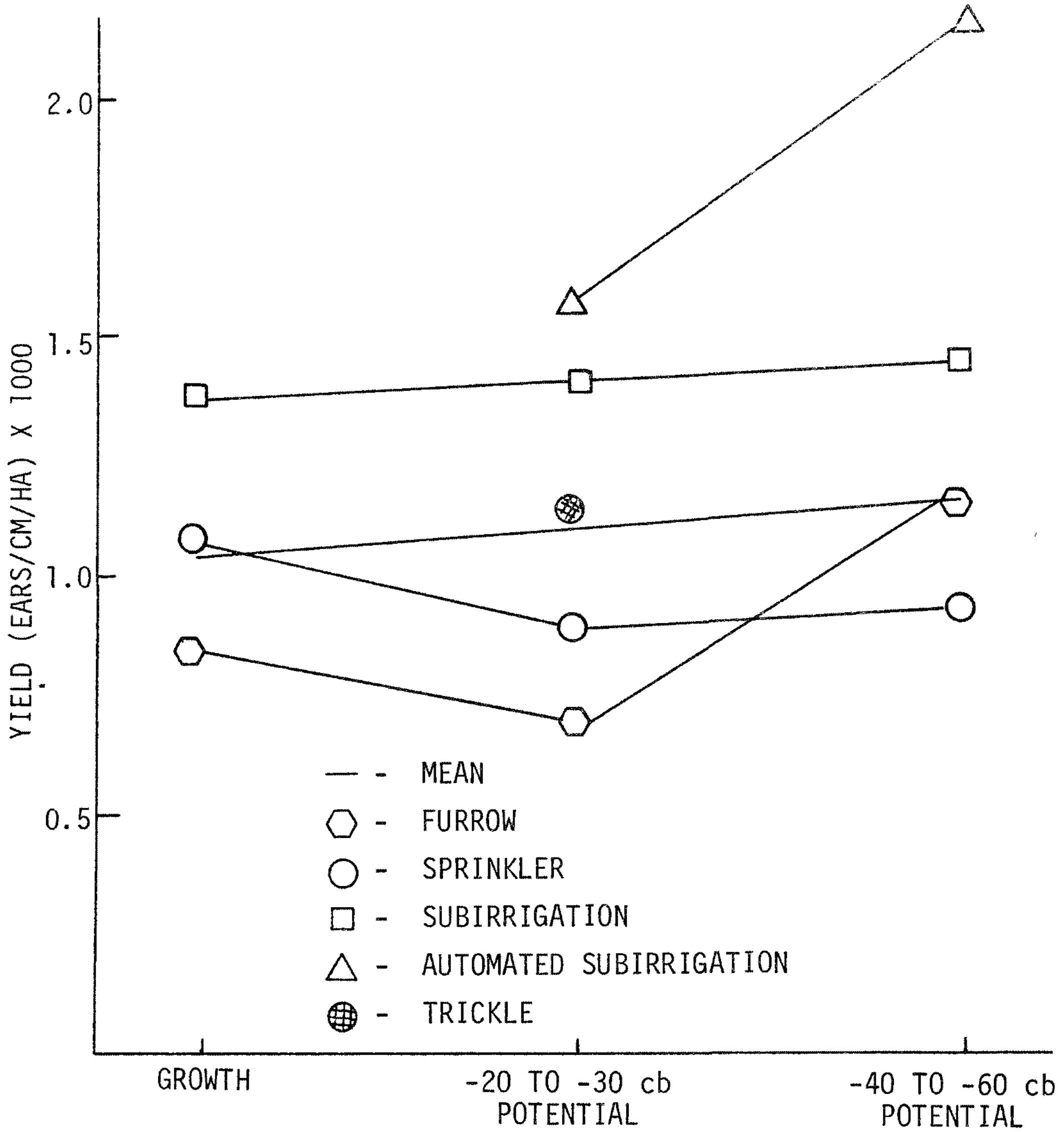


Figure 193. Yield of sweet corn per cm water as influenced by different criteria for applying irrigation water, 1971-1974, Knox County, Texas.

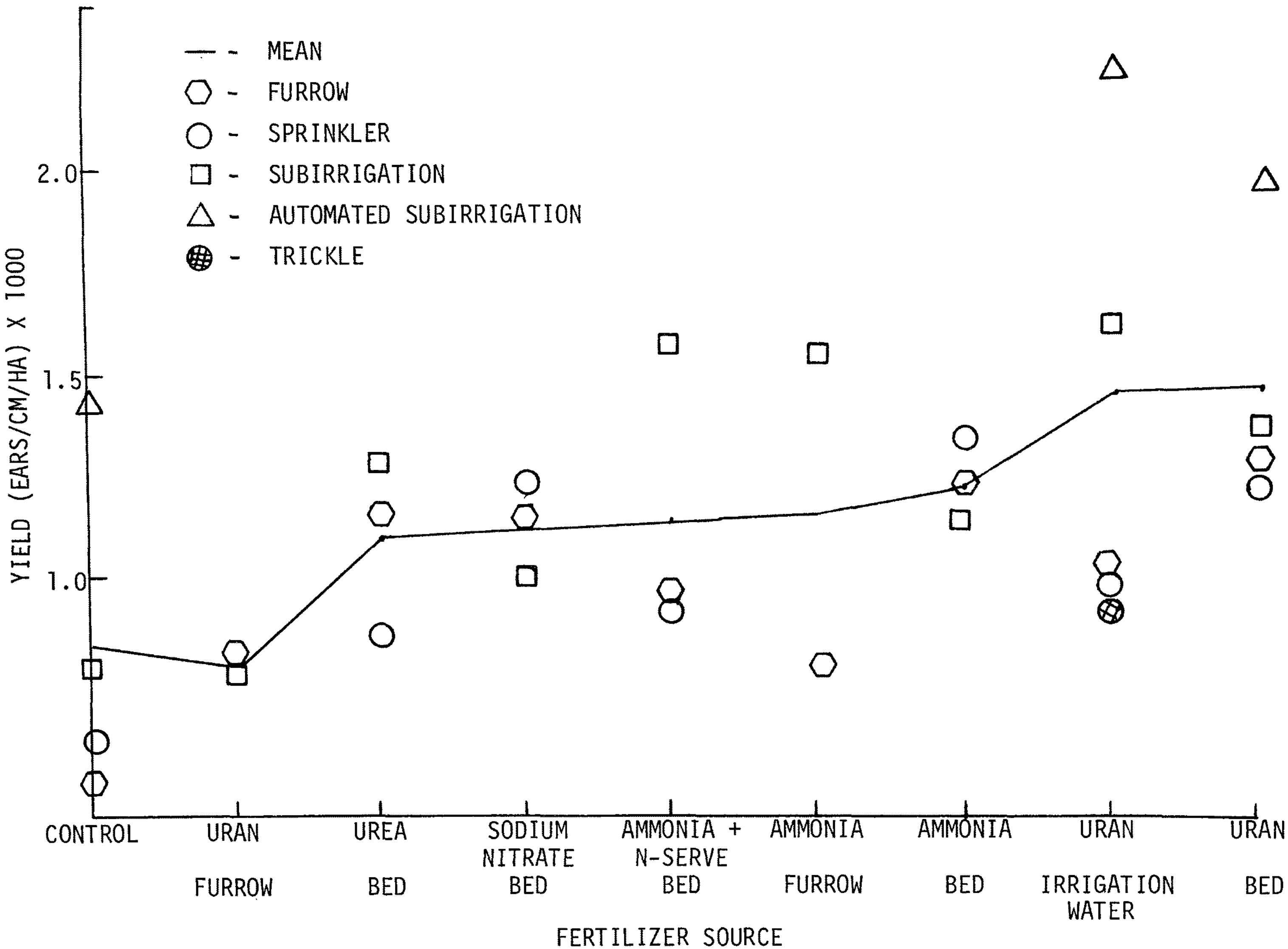


Figure 194. Yield of sweet corn per cm of water of different irrigation systems as influenced by different fertilizer sources and methods of application, 1971-1974, Knox County, Texas.

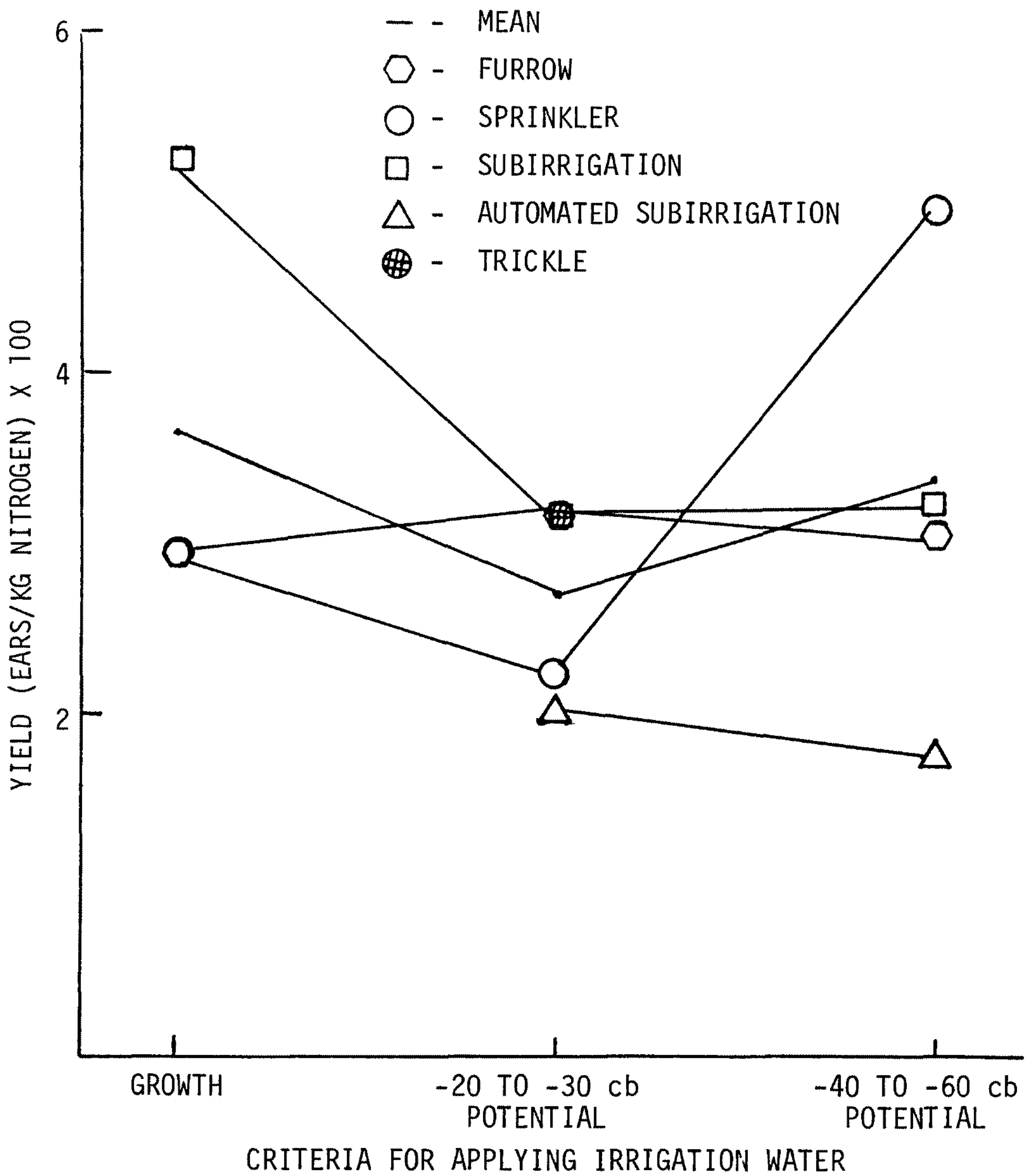


Figure 195. Yield of sweet corn of different irrigation systems per kg of nitrogen applied at the 100 kg/ha rate as influenced by different irrigation criteria, 1971-1974, Knox County, Texas.

furrow plots, and lowest from the automatically-subirrigated plots. Figure 196 shows there was little influence of fertilizer source or method of application on the yield per unit of nitrogen where 100 kg/ha were applied to all treatments.

Where 22.5 kg of nitrogen were applied per ha, there were major differences in the yield per unit of fertilizer applied (Figure 197). Yields/kg of nitrogen of the different irrigation systems from the -20 cb plots were superior to those of the -40 cb plots except for the automatically-subirrigated plots. In the -20 cb plot system, yields per unit of nitrogen from the furrow irrigation system were the highest, followed by yields of the sprinkler system and automated subirrigation systems, with the lowest yields being obtained from the subirrigated plots. In the -40 cb plots, highest yields/unit of nitrogen were obtained from the automated subirrigation system followed by the furrow and sprinkler systems with the subirrigation systems again have the lowest efficiency. However, it should be pointed out that, although the yields per unit of nitrogen are higher for the 22.5 kg application rate, the highest yields were obtained with the application of the highest rates of nitrogen.

In summary, when sources of fertilizer were applied at 100 kg/ha rates, there was no significant difference in the yield per unit of nitrogen. Differences among irrigation systems existed when less than optimal amounts of nitrogen were applied in the irrigation water. However, maximum yields were not obtained.

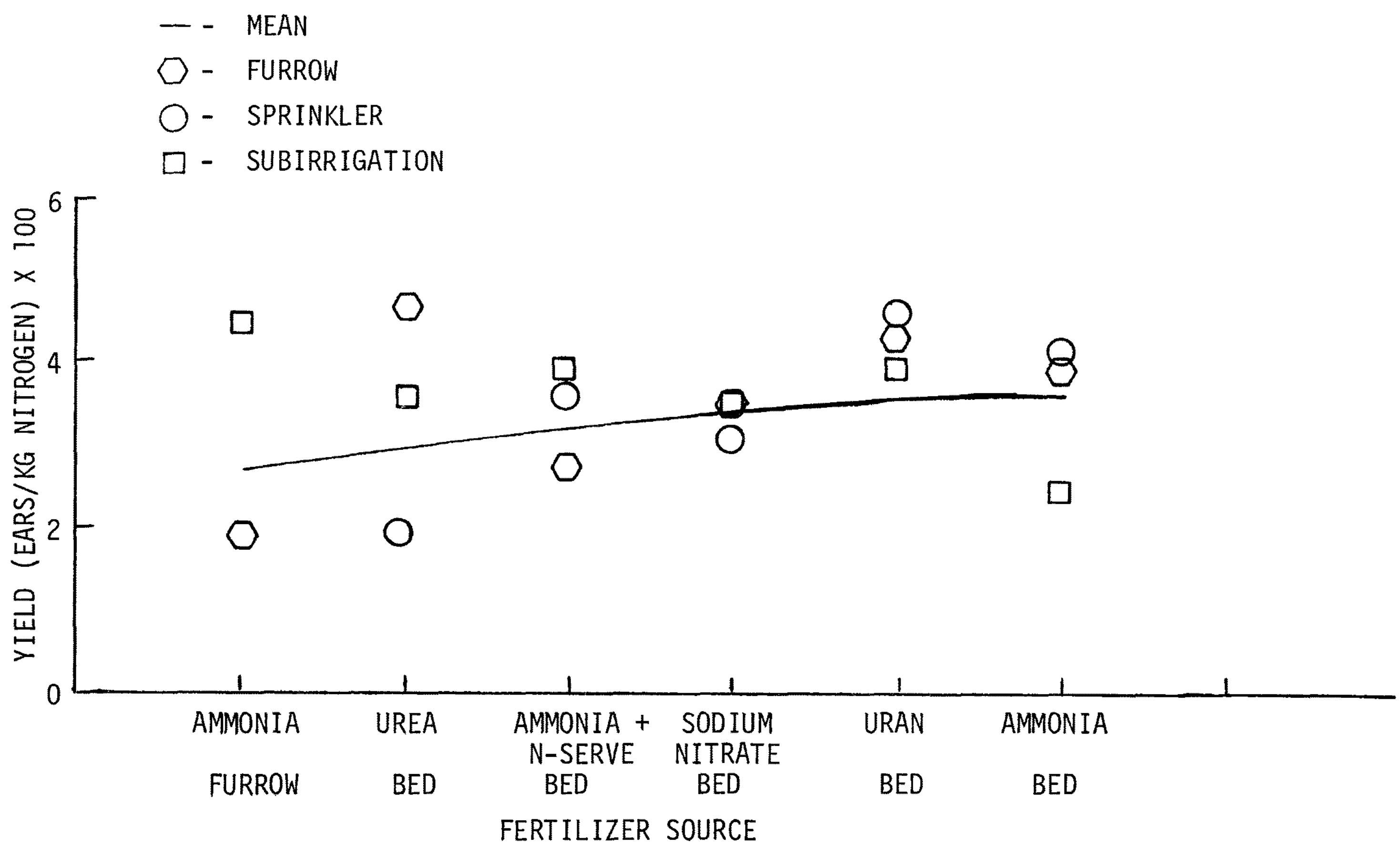


Figure 196. Yield of sweet corn of different irrigation systems per kg of nitrogen applied at the 100 kg/ha rate as influenced by different fertilizer sources, 1971-1974.

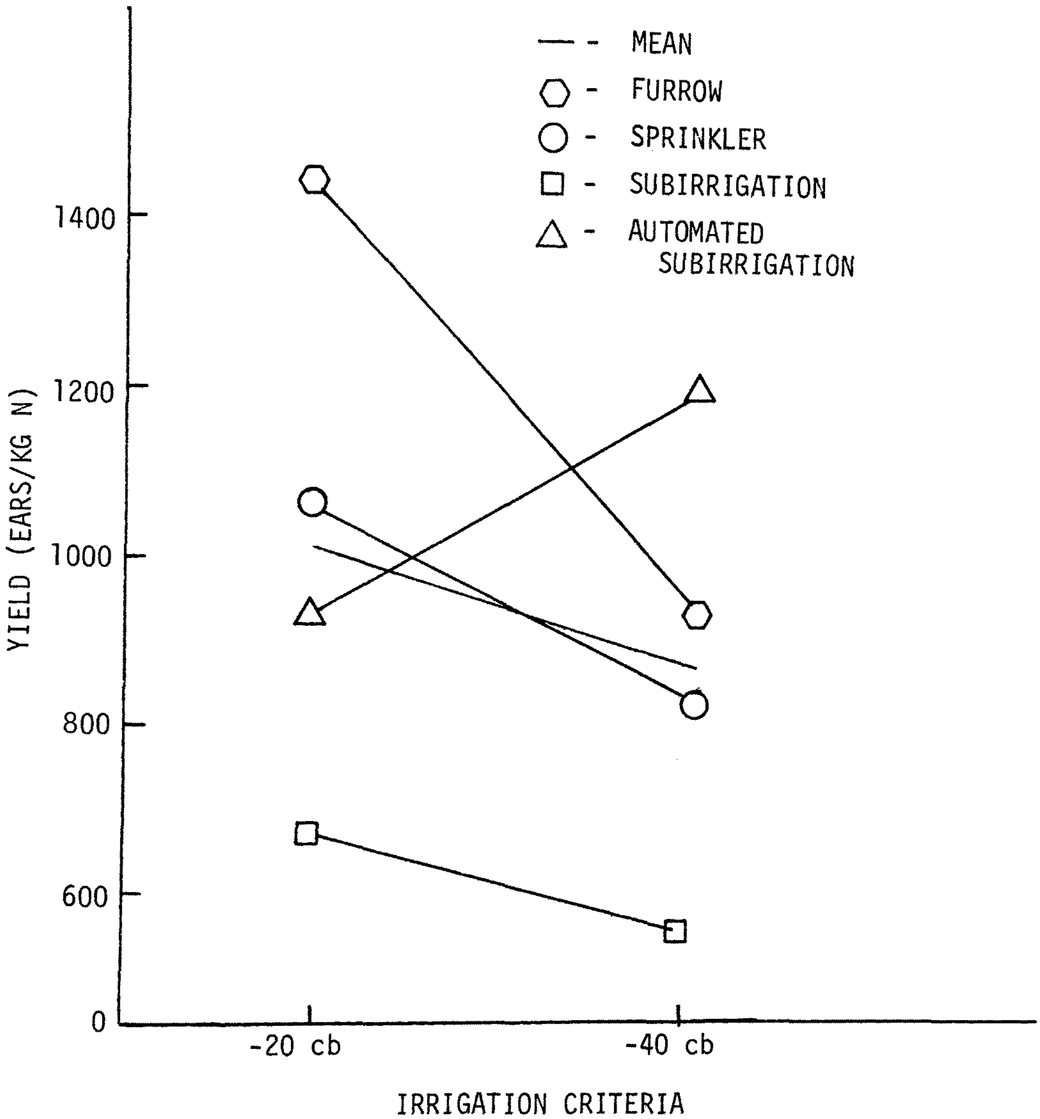


Figure 197. Yield of sweet corn of different irrigation systems per kg of nitrogen applied at the 22.5 kg/ha rate as influenced by the different irrigation criteria, 1971-1974.

SECTION 7

SUMMARY

A comparison of sprinkler, furrow, and manual subirrigation systems showed that nitrate-N in soil samples and porous bulb extracts was much less for samples from below the root zone from subirrigation systems than from the sprinkler or furrow systems. Through analyses of ^{15}N in soil and plant materials it was possible to account for 92.6%, 86.1%, and 50.5%, respectively, of the fertilizer nitrogen applied to the sprinkler, furrow, and subirrigation systems over a two-year period. Soil-water potential, bromide tracer, porous bulb extract, and soil data all support the idea that denitrification occurs with subirrigation systems in that the major differences between systems was the amount of soil nitrogen that could be detected. In any case, less nitrate-N was available to be leached in the subirrigated plots.

Where fertilizer was applied each year, 62%, 55%, and 49% of the fertilizer was used by corn from the sprinkler, furrow, and subirrigation systems, respectively. As there was little difference in yield, the data indicate that more than adequate fertilizer was applied even though the uptake percentages were different. The crop contained 2.0%, 3.6%, and 7.4% of the fertilizer applied the previous year when grown under sprinkler, furrow, and subirrigation, respectively. These data indicate that much of the nitrogen from the previous year's crop was still in the organic form in that only small amounts were available.

Movement of nitrate during and between growing seasons was noted, especially with the furrow and sprinkler irrigation plots. Data from ^{15}N and bromide tracer studies showed unique patterns of movement for the different systems. Banded fertilizer moved vertically as discrete bands under the sprinkler irrigation system. In the furrow irrigation system, the fertilizer bands merged in the bed and then moved vertically. Fertilizer bands moved up and away from the buried subirrigation system. In addition to being influenced by irrigation system, the downward movement was influenced by soil texture and the rainfall received between growing seasons.

By irrigating on the basis of potential ET, it was possible to maintain nitrogen fertilizers in the root zone during the growing season. The ranking of systems relative to irrigation water requirement was furrow > sprinkler ≅ subirrigation > automatic subirrigation. In general, the automated subirrigation system required water applications of only 50% to 60% of the sprinkler and manual subirrigation systems and 30% to 40% of the furrow system. During the study only 10 to 14 cm/year of supplemental water were applied through the automated system to produce the sweet corn crop, compared to 18 to 38 cm/year applied through the other systems. However, the differences among systems relative to the total amount of water used by the crop was not significant. Where less irrigation water was applied, more of the soil water was used. The studies showed that the plots with automated subirrigation maintained a portion of the soil profile (0 to 45 cm) with adequate moisture through frequent irrigations of 0.25 cm or less and allowed the zone below 45 cm to dry. This created a zone for storage of rainfall and substantial increases in irrigation water-use efficiency. The model of Jensen, et al. (10) for ET potential combined with the ET at various LAI by Ritchie and Burnett (21) proved adequate for estimating crop water requirements.

There was no difference in irrigation water requirement between systems when irrigations were made on the basis of potential ET, if the system was well designed. It was difficult to apply water in small amounts with the furrow irrigation system on the loamy fine sand soil. Consequently, the water added was greater than that indicated by potential ET. However, as previously discussed, the irrigation water requirement of the automated subirrigation system was significantly less than those of other systems even though they were irrigated based on potential ET.

Solutes other than nitrate-N were measured to determine if their concentration was influenced by irrigation system. Measurements were made of nitrite, phosphate, chloride, sulfate, sodium, calcium, magnesium, ammonium and potassium concentrations and conductivity. Nitrite and phosphate measurements were discontinued after the first year due to low concentrations. Porous bulb extracts from subirrigation systems were lower in chloride, sulfate, sodium, calcium, and magnesium concentrations and conductivity than the furrow and sprinkler irrigation systems. The concentrations of the above-mentioned ions and conductivity of extracts from the automated subirrigation system were significantly lower than extracts from the other systems. In no case was there an indication of any of these ions being a problem in degradation of irrigation return flow in that the ion concentrations and the conductivity of extracts in most cases were only slightly higher or less than the ion concentrations and conductivity of the irrigation water. The data do suggest, however, that manual and automatic subirrigation may have the potential to enhance the quality of irrigation return flows because a) the concentrations of ions and conductivity were significantly lower in the application zone around the subirrigation pipe and b) significantly less water was added through the automated subirrigation system; therefore, significantly less salt was added.

Potassium was lowest in the furrow system due to land leveling. The ion was indicated to be made available at a constant rate throughout the growing season.

Although significant concentrations of ammonium were found periodically, there was no consistent pattern relative to amount, location, and time so that conclusions cannot be made concerning its presence.

The automated subirrigation system applied less water, but also produced less total sweet corn yield. However, the yield per unit of water of the automated subirrigation system was significantly higher than the other irrigation systems. Total yields of the manual subirrigation, furrow irrigation, and sprinkler irrigation systems were approximately equal. The manual subirrigation system was more efficient (yield/unit of water) than the sprinkler and furrow systems. There was no difference in nitrogen-use efficiency (ears of corn/kg/ha) when 100 kg/ha/year were applied. When only small amounts of nitrogen were applied (22.5 kg/ha), the manual subirrigation system was less efficient than the other systems.

Although subirrigation systems show promise relative to enhancing the quality of irrigation return flows and increasing water-use efficiency, problems exist with the systems. The cost of the systems is high. Net returns for the sprinkler, furrow, manual subirrigation, and automated subirrigation were $166, $180, -$88, and -$172.90/ha, respectively. For the subirrigation system to compete with the sprinkler and furrow systems, it would have to cost, respectively, only $528 and $407/ha, compared to the current cost of $2,470/ha. The $2,780/ha cost of the automated subirrigation system would need to be decreased to $432 and $311/ha, respectively, to compete with the sprinkler and furrow systems. Yields of the manual subirrigation and automated subirrigation systems would need to be increased 33% and 50%, respectively, to compete with current furrow and sprinkler irrigation systems.

Other problems with subirrigation systems include obtaining emergence with bed planting, movement of banded fertilizer from the active root zone, stoppage of orifices due to roots and soil particles, and miscellaneous problems relative to gophers, valves, splitting pipes, and filtering. However, none of these are technically insurmountable.

Criteria used to apply irrigation water were a) curling of upper leaves at midday, b) -20 cb soil-water potential at 30 cm, and c) -40 cb soil-water potential at 30 cm. No differences in quality of irrigation return flow were noted from using the different criteria. Total yield of sweet corn was greater when the plots were irrigated at -20 cb potential than at -40 cb or at leaf curling. No differences in yield/unit of water were noted from using the different criteria. Yield/unit of nitrogen applied was greater when the plots were irrigated at leaf curl and -40 cb potential than at -20 cb potential.

Methods of fertilizer application evaluated in the studies were banded below the level of the water furrow, banded above the level of the water furrow, and applied through the irrigation water. In the furrow irrigation system, the nitrate-N concentrations in soil samples and porous bulb samples from below the root zone were higher where the fertilizer was banded below the level of the water furrow. Significant losses of nitrogen occurred when applied through the water in the sprinkler and subirrigation systems. Much of the nitrogen banded over the subirrigation systems was not detected for reasons previously discussed. However, since high rates of nitrogen were applied, no differences were observed in yield/unit of water or yield/unit of nitrogen due to method of application.

Sources of fertilizer used in the study included anhydrous ammonia, Uran, sulfur-coated urea, and ammonia + N-Serve. There was no distinct advantage of any source relative to nitrate-N in irrigation return flows, total yield, yield/unit of water, or yield/unit of nitrogen.

The model by Hillel, et al. (9) for determining hydraulic conductivity was evaluated. Values obtained varied for the same texture at different depths and for the same depth for a given soil-water content and matric potential when determined more than one time at the same location. Changes of 100-fold in values for hydraulic conductivity occurred with 2% to 6% changes in soil-water content. Water movement occurred within the soil profile due to saturated pressure heads as well as unsaturated pressure gradients.

Due to the problems with the above-mentioned variability, a regression model was developed for hydraulic conductivity as a function of moisture content, depth, and texture. The r value for the equation was .915. However, the standard error of estimate was so great that further use of the equation was not deemed worthwhile.

An empirical model for nitrate movement as a function of rainfall, irrigation, fertilization, potential ET, LAI, uptake of nitrogen by the crop, and the relationship for calculating ET as a function of leaf area was devised using data obtained at the site. The most important parameters were found to be the amount of irrigation water applied and total nitrate in the profile. When water applied was greater than 2 to 2.5 x potential ET and nitrate-N in the profile was greater than 200 kg/ha, the leachate concentration was greater than 20 ppm nitrate-N. When irrigation water amounts were equal to potential ET, no nitrate-N was leached. Less nitrogen was needed when irrigation water applications and rainfall equalled potential ET. In the absence of excess rainfall, automated irrigation will keep nitrate-N in the root zone. Turning under residue while the soil is still warm in the summer will enhance nitrification and add nitrate-N to the leachate.

Bromide was found to be an excellent indicator of nitrate movement. An excellent relationship was found between bromide depth and net water added to the soil ($R = .879$). The relationship indicates that for each cm of excess water added bromide or nitrate will move down 7.4 cm.

Some of the site characteristics are worthy of note in that they influence parameters related to irrigation return flow. The soil at the site is relatively uniform at the surface but varies considerably in texture and bulk density with depth. The layering causes the soil to have a large amount of water at field capacity (-10 cb instead of -33 cb). An excess of water is needed to cause movement from one layer to the next. Highest water contents and nitrate concentrations were found in or above zones of higher clay content. The soils are self-mulching so that adequate planting moisture can be stored for 6 to 8 months, thus decreasing the irrigation water requirement for emergence.

Some of the site characteristics are of interest since they may affect water quality and irrigation return flows. The clay minerals are interstratified mixtures of montmorillonite and illite and are the same from the surface to the water table. Wells at the site received horizontal recharge from the local aquifer. Large amounts of nitrate were found in soil-water extracts (>50 ppm nitrate-N) on the control plots. Data from the ^{15}N studies show that the corn crop used 50 kg of nitrogen/ha from soil nitrogen. Rainfall received during the study ranged from 483.0 to 596.2 mm for 112.9-mm variation. Rainfall during growing seasons varied from 104.0 to 224.7 mm for a difference of 120 mm. Rainfall between growing seasons of sweet corn was 2 to 4 times that received during the growing season. These variations emphasize the importance of using some criteria other than stage of growth for timing of irrigations and some method of determining amounts to be applied in order to maintain the quality of irrigation return flows with respect to nitrogen.

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MANUSCRIPTS PREPARED AND SUBMITTED

1. Bausch, W., A. B. Onken, C. W. Wendt, and O. C. Wilke. A Self-propelled High-clearance Soil Coring Machine. Submitted to the Agronomy Journal.

2. Onken, A. B., C. W. Wendt, R. S. Hargrove, and O. C. Wilke. Relative Movement of Bromide and Nitrate Under Three Irrigation Systems. Submitted to Soil Science Society of America Journal.

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16. ABSTRACT Sprinkler irrigation, furrow irrigation, subirrigation, automated subirrigation, criteria for applying irrigation water, methods of applying fertilizer and sources of fertilizer were investigated as to their potential to decrease possible pollution from nitrate and other solutes in a loamy fine sand soil overlying a shallow aquifer in Knox County, Texas.

Less nitrate-nitrogen was available for leaching in subirrigation systems than furrow and sprinkler systems. Less irrigation water was applied with automated subirrigation systems than with the other irrigation systems. However, crop water requirement was not significantly changed--the soil water was more efficiently used. Fertilizer remained in the root zone if the water applied was based on potential evapotranspiration and leaf area regardless of the irrigation system or the criteria used to apply the irrigation water. Banded fertilizers moved differently in the different irrigation systems.

Subirrigation has the possibility of having irrigation return flow with lower concentrations of other solutes than sprinkler or furrow systems.

Banding fertilizer in the bed was superior to banding below the level of the water furrow and applications in the irrigation water relative to quality of irrigation return flow. No other source of nitrogen fertilizer was indicated to be superior.

Current fertilization practices are not causing major increases in the nitrate-nitrogen level in the aquifer.

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