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TIME DOMAIN REFLECTOMETRY BASED

TURFGRASS IRRIGATION SCHEDULING

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Michael Thomas Saffel

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P. E. Rieke
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By

Michael Thomas Saffel

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ABSTRACT

TIME DOMAIN REFLECTOMETRY BASED
TURFGRASS IRRIGATION SCHEDULING

BY

Michael T. Saffel

Time domain reflectometry (TDR) was used to determine daily volumetric soil moisture changes in fairway turfs for predicting irrigation programming. Irrigation blocks were split into adjacent 5.5m by 11m sections which were planted with annual bluegrass [*Poa annua* var. *reptans* (Hausskn.) Timm.] or Penncross creeping bentgrass (*Agrostis palustris* Huds.). Three irrigation regimes were utilized in the study: irrigating daily returning to field capacity; 2.5mm per day; and irrigating when stress appeared. TDR probes were placed horizontally to measure the 0-5cm, 5-10cm, 10-15cm and 15-25cm zones. Correlation coefficients between gravimetric and volumetric (TDR) soil moisture measurements ranged from .83 to .90. Each species was evaluated for quality, rooting and clipping weights in 1991. Field capacity treatment soil moistures were higher than desirable. The 2.5mm daily treatment provided acceptable quality for bentgrass and annual bluegrass. Bentgrass performed better under moisture limiting conditions than did annual bluegrass.

To Julie, Will and Thomas
thank you

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INTRODUCTION

Available, affordable, high quality irrigation water is becoming increasingly difficult to obtain for turfgrass use in many regions. The present method of scheduling irrigation relies on the turfgrass manager's experience and observations. Information and tools are needed to aid the turfgrass manager with efficient irrigation. However, increased efficiency must maintain high quality turfgrass.

Effective turfgrass irrigation scheduling is an active topic of research. Excessive irrigation is a major problem facing the turfgrass industry. Irrigation scheduling has been hampered by the lack of soil moisture measurement devices that provide information that can be directly used to determine irrigation amounts.

One goal of this work was to adapt and test Time Domain Reflectometry (TDR) for fast, frequent volumetric soil moisture measurements. With accurate volumetric soil moisture measurements and irrigation application rates, irrigation systems can be set to apply only the amount needed to return the soil to a proper moisture level.

A second goal of the study was to evaluate Penncross creeping bentgrass (*Agrostis palustris* Huds.) and annual bluegrass [*Poa annua* var. *reptans* (Hausskn.) Timm.] at fairway height, 1.27cm, under three irrigation philosophies; maintained daily at field capacity, .25cm daily applied daily and irrigation upon appearance of stress. Emphasis was placed on duplicating actual field conditions as closely as possible.

LITERATURE REVIEW

Turfgrass Irrigation Scheduling

The effort to provide turf managers with guidelines for proper rates and timing of irrigation has lead researchers to many methods of estimating turfgrass water use.

One approach was to irrigate on selected days and times of day and evaluate turfgrass responses. The effect of irrigation and nitrogen rates on the incidence of pink snow mold was evaluated (Madison, et al. 1960). In this study three irrigation intervals and two times were evaluated. Irrigation intervals were every day, three times per week and once per week. The two times were from 7-8 a.m. and 7-8 p.m. A total of 4.6cm per week was applied to all plots. Irrigation did not affect the incidence of snow mold.

In another study designed to investigate the effects of interval scheduled irrigation, nitrogen rates and sources and mowing heights, Madison (1962), found that frequent irrigation (five times weekly) increased turf density and increased nitrogen efficiency from ureaformaldehyde. However, these increases were offset by decreases in rooting, dry weight, verdure, chlorophyll and yield. The frequent irrigation treatment resulted in higher soil moisture contents. When irrigation practices were changed from infrequent to frequent an immediate improvement in turf quality was observed as new growth was stimulated. Madison concludes that the initial improvement in quality from frequent irrigation may not lead to long term quality.

Peacock and Dudeck (1985) used irrigation treatment intervals of 2,3,4 or 6 days to apply amounts equal to 0.64 cm day^{-1} in 1980 and 0.38 cm day^{-1} in 1981, as a means of evaluating the effects of the irrigation treatments on St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] rooting. The interval changed but an equal volume of water was applied in each treatment. Initial and final root samples were taken in 15 cm increments to 75 cm from field plots. The results of their study showed no difference in rooting for the irrigation treatments in either year. However, there was an increase in total root weight in 1981 compared to 1980.

In the same study by the Peacock and Dudeck (1984) also studied the effects of the 2,3,4, and 6 day irrigation intervals to evaluate the physiological responses of St. Augustinegrass to these different irrigation schedules. Evapotranspiration rate, carbon dioxide exchange ratio, leaf water potential, and leaf diffusive resistance were not different for the 2,3, and 4 day treatments. The 6 day interval treatment showed lower evapotranspiration, greater leaf diffusive resistance, a lower carbon dioxide exchange ratio and lower leaf water potential than the other treatments. Quality was not different among treatments.

While rooting and physiological measurements provide valuable information on the responses of St. Augustinegrass to the different irrigation schedules, the data collected do not provide much practical information for determining irrigation amounts.

Biran et al. (1981) used usual and dry irrigation treatments on warm and cool season turfgrasses. The usual treatment was irrigation to 20 to 40% more than the soil depletion every 2 or 3 days for both grasses. The dry treatment was 20 to 40% more than soil moisture depletion once weekly for the warm season grasses, and 3 irrigations in a 2 week period, for the cool season grasses. The dry treatment required less water and produced less dry matter. For both treatments, the warm season grasses had lower water consumption than the cool season grasses. The less frequent irrigation schedule supported the findings of Feldake et al. (1983) who reported that irrigation of lawn grasses when wilt becomes apparent saves water. More water was used by the grass when mowed at 6 cm than at 3 cm. When transpiration rates of species and cultivars were evaluated grasses with deeper root systems had a greater ability to extract moisture at lower soil moisture tensions. *Zoysia matrella* was more sensitive to low soil moisture potentials than tall fescue (*Festuca arundinacea* var alta), bermudagrass or St. Augustine. The shallow root system of *Zoysia matrella* is not able to extract moisture as well as the deep rooted tall fescue (Beard, 1973). Photosynthesis was also decreased with decreasing soil moisture potential.

Open pan evaporation percentages have been used by many to estimate turfgrass water requirements (Gaussoin and Branham 1989). To be used effectively a class A weather evaporation pan should be located in a site similar to the area studied. The amount of water lost from the free water surface surface is adjusted to more closely represent turfgrass evapotranspiration. Doorenbos and Pruitt (1977) recommend an adjustment factor of .85 for forage grasses. This factor is for an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, which is actively growing, completely shading the ground and not in a water limiting condition. This height of turf and soil moisture conditions are not common in practice in turf management, but provide a baseline for estimating water loss from turf areas.

Gaussion and Branham (1989) used irrigation treatments of 75% open pan replaced daily, 110% open pan triweekly, and irrigation at wilt treatments to evaluate annual bluegrass and creeping bentgrass competition under fairway conditions. They found that daily 75% open pan evaporation combined with annual overseeding of creeping bentgrass increased creeping bentgrass in a mixed stand of annual bluegrass/creeping bentgrass. Without overseeding, irrigation at 75% open pan evaporation increased the percent of annual bluegrass in the stand.

Estimated evapotranspiration (ET) is widely used as a method for scheduling irrigation. Several irrigation companies offer weather stations that use the Penman equation (1948) for estimating irrigation needs. A modified Penman equation described by Rosenberg et al. (1983) uses a wide range of atmospheric data to calculate water loss. Pan coefficients (Carrow, 1991; Aronson, et al. 1987a) and crop coefficients (Shearman, 1989; Carrow, 1991) can also be used with the Penman equation to more closely estimate the water needs of the specific turfgrass application. Pan coefficients are empirically derived. The crop coefficient (Kc) is the actual evapotranspiration (Ka) divided by estimated evapotranspiration. Actual ET is determined with weighing lysimeters (Feldhake et al., 1984; Kim and Beard, 1988; Shearman 1986, 1989; Aronson et al., 1987a; Aronson et al., 1987b). As an empirically derived coefficient the pan coefficient has wide variability. The limitation to the use of crop coefficients is that turfgrasses vary widely among species (Kim and Beard, 1988), within species (Shearman, 1986; Shearman, 1989), and during a growing season (Aronson et al., 1987a; Carrow, 1991) and by geographic region. Because of the wide range of actual ET the use of this data can serve only as a guideline.

Infrared thermometry has been used to measure canopy temperatures in alfalfa (Idso et al., 1981) and turfgrass (Throssell et al., 1987). In the turfgrass study, canopy temperatures were measured with infrared thermometry in order to determine crop water stress index (CWSI), stress degree days (SDD) and critical point model (CPM). These measurements were then used to schedule irrigation events.

The effectiveness of these methods was compared to tensiometer based irrigation schedules. The CWSI compares vapor pressure deficit to temperature differences between canopy temperature and air temperature. The CWSI ranges from 0 to 1 and as it increases plant stress increases. Canopy temperatures are used to calculate the number of Stress Degree Days (SDD). A predetermined number of SDD (10) were evaluated against the other treatments. The Critical Point Method (CPM), is quite complex and uses soil moisture data, atmospheric data, open pan evaporation and number of days between irrigation events to determine irrigation scheduling. The SDD method requires calibration for each site and season. This makes SDD scheduling difficult. The CWSI and CPM methods are not site specific. CWSI is based upon nonlimiting soil water. CPM uses atmospheric data and thus reacts well to weather changes that affect turf water demands. All methods require that a degree of stress or soil moisture depletion be predetermined. This predetermination limits their usefulness as the degree of acceptable stress may vary by season and turfgrass application. The tensiometer based irrigation schedule was the most successful (Throssel, et al., 1987).

Tensiometers have been used to evaluate turfgrass irrigation schedules (Augustin and Snyder, 1984; Letey, et al., 1966). Letey et al. (1966) found tensiometer scheduled irrigation superior to set calendar irrigation. Tensiometer scheduled irrigation produced more roots than calendar set irrigation on compacted and noncompacted soils.

Augustin and Snyder (1984) showed significant water savings, in bermudagrass (*Cynodonn dactylon X C. transvaalensis*) turf, using tensiometers compared to calendar set irrigation. Water savings from tensiometer-based irrigation were between 42% and 95% compared to daily irrigation based on evapotranspiration estimates. The tensiometer plots were irrigated when soil moisture reached a predetermined level. When this soil moisture level was reached an irrigation timer was activated and a set amount of water applied. The reasoning for the amount applied, when the tensiometers reached the level indicating irrigation was warranted, was not presented in the paper. The tensiometer scheduled plots received 26% as much water compared to the daily treatment plots. The greatest savings came during periods of frequent but unpredictable rainfall. The savings were largely due to the elimination of irrigation events. In this study there were no turf quality differences between irrigation treatments.

Others (Agnew and Carrow, 1985; Aronson, et al., 1987b) have used tensiometers to measure turfgrass soil water potential but did not use the measurements for scheduling irrigation. Tensiometers have several limitations (Hillel, 1982). Tensiometers measure the energy potential of the soil water. This data is useful for determining how much water to apply only when a reliable moisture release curve is available for the specific soil. In turfgrass maintenance the physical properties of the soil may change during the year, because of traffic, compaction and cultivation.

Tensiometers require regular maintenance and must be replaced at the beginning of each growing season in cold climates where they would be subject to freezing. The porous ceramic cup is permeable to both water and solutes. In high salt content soils where osmotic potential may affect water availability tensiometers may not be accurate. Considerable time is required for the tensiometers to equilibrate with the soil water after a moisture event. When irrigation scheduling decisions must be made at a point in time this may be a limitation.

The neutron probe was used by Peacock and Dudeck (1985) to monitor soil moisture in their study of irrigation scheduling effects on St. Augustinegrass. The neutron probe method measures volumetric soil moisture. It has advantages over gravimetric sampling, being less labor intensive, rapid and nondestructive. The limitations are that it is expensive, has a low degree of spatial resolution, does not measure surface zones well and poses a potential health hazard from possible exposure to neutron and gamma radiation (Hillel, 1982). The low degree of spatial resolution and inability to measure soil moisture near the surface present limitations for turfgrass applications. The potential radiation hazard restricts the use of the neutron probe to qualified, highly trained individuals.

Time Domain Reflectometry

The use of Time Domain Reflectometry is being used in turfgrass studies to determine volumetric soil moisture content under varied conditions (Carrow, 1991).

Time Domain Reflectometry (TDR) has become an accepted method for measuring volumetric soil moisture content (Baker and Lascano, 1989). For irrigation scheduling, the measurement of volumetric soil moisture is advantageous. It supplies data that can be readily converted to amount of irrigation to be applied.

TDR volumetric soil moisture determinations use measurements of the properties of electromagnetic waves (Topp and Davis, 1985). The propagation velocity and attenuation of these waves depend on soil properties, especially the water content (Topp, 1987). The propagation velocity and the amplitude of the wave are used to determine volumetric soil moisture. The electromagnetic wave is sent from the TDR to parallel wave guides in the soil (Baker and Lascano, 1989; Topp and Davis, 1985). Wave guides are often connected to the TDR by shielded antennae wire, an impedance matching balun and a coaxial cable. There is a partial reflection of the signal at the connection of the wave guides and the antennae wire with the remainder of the signal being reflected at the open circuit at the ends of the wave guides. The distance between these reflection points, as measured on the TDR wave, is a function of the permittivity of the soil, which is used in determination of the volumetric soil moisture content (Baker and Lascano, 1989). As the distance between the reflections increase, soil moisture content increases. The TDR measures time, and the length of the wave guides are known, from which wave velocity is determined. The velocity of the wave is related to the apparent dielectric constant, K_a, of the soil (Topp et al., 1980). An approximate relationship between the signal propagation, v, and the dielectric constant, K_a, is

$$v = \frac{c}{K_a^{1/2}} \qquad (1)$$

where c is the velocity of an electromagnetic wave, 3×10^8 meters per second. Calculation of propagation velocity is determined from using the distance traveled by the wave (2 times the length of the wave guides) and the signal travel time in the soil, t, as measured by the TDR. Calculation of K_a is then possible from substitution and rearrangement of the above equation to:

$$K_a = \left(\frac{c}{v}\right)^2 = \left(\frac{ct}{2L}\right)^2 \qquad (2)$$

The dielectric constant of water is approximately 80 and of soil is between 2 and 5. An increase in the dielectric constant of the measured soil medium is primarily due the increase in water content of the soil. Topp et al.(1980) found that when TDR signals were sent through coaxial transmission lines the measured soil dielectric constant related to volumetric soil moisture by the following relationship;

$$\theta_v = -0.053 + 0.0292K_a - 5.5x10^{-4}K_a^2 + 4.3x10^{-6}K_a^3 \quad (3)$$

where O_v is volumetric soil moisture content. An important point of their research is that the relationship is independent of electrical conductivity, bulk density, temperature and mineral composition. This means the above equation can be used to determine soil moisture on many different soils. The measurements had an accuracy of 0.02 m^3 m^{-3} and a precision of 0.01 m^3 m^{-3} (Topp, 1987). Topp and Davis (1985) found that TDR measurements were as reliable as gravimetric sampling for determining volumetric soil moisture content.

Several different probe orientations have been investigated. Topp and Davis (1985) found that vertically installed wave guides have the following advantages: easy installation and removal, and measurement of the total water over the length of the wave guides. Horizontal wave guides better integrate the spatial variability in the soil. Carrow (1991) placed the wave guides at 45° angles with success.

The influence of the number of wave guides and their arrangement has also been studied. As the number of wave guides was increased the area of measurement and accuracy increased (Zegelin, et al., 1989). By increasing the number of parallel wave guides from two to three, improvements in volumetric soil moisture determinations occurred. However, when four guides were used in a triangular pattern with the fourth probe in the center, little improvement was seen.

Baker and Lascano (1989) studied the spatial sensitivity of TDR to water in air and water. Air and water measurements were used as they approximate the extreme ranges of soil moisture. The shape of the area of influence is between elliptical and rectangular. When placed horizontally, the greatest area of influence is approximately 1000 mm^2 with decreasing resolution to 3600 mm^2. The area of greatest sensitivity is from the wave guide to 15 mm around the probe, with some influence to 40 mm. This information indicates that wave guides could be place in the horizontal, 20 mm from the surface.

It is evident that the ease, accuracy and safety of TDR measurements make it an ideal tool for turfgrass irrigation evaluations. With continued use and improvement of this technique turfgrass researchers will be able to measure volumetric soil moisture under a wide variety of conditions. TDR does not require soil moisture release curves that are necessary when using tensiometers, gypsum blocks and nylon wafers. TDR has an advantage over the neutron probe as radioactive materials are not involved, it is sensitive to soil spatial variability and TDR has the ability to measure soil moisture in zones near the surface.

MATERIALS AND METHODS

Objectives and Experimental Design

This study has two goals: first, to adapt and test Time Domain Reflectometry (TDR) as an effective tool for irrigation scheduling of turfgrasses; second, to measure responses of annual bluegrass and Penncross creeping bentgrass responses to three irrigation schedules: maintained daily at field capacity; .25 cm applied daily (Vargas, 1994); and irrigation back to field capacity upon the appearance of wilt.

Nine 12.2m by 12.2m plots were assigned to this study. At the four corners of these plots Rainbird Maxipaw (Rainbird Company, Glendale CA.) sprinklers with 12.5 liter per minute nozzles were installed, creating nine irrigation plots. Within these plots an area 11m by 11m was split by species, 5.5m by 11m each, one being annual bluegrass the other and creeping bentgrass. TDR probes were installed horizontally to measure soil moisture in the following depth zones: 0-5 cm, 5-10 cm, 10-15 cm and 15-25 cm. This design is a split-split plot design with whole plots arranged in a three treatment, three replication randomized block design. Irrigation treatments are the whole plots, the species are split within irrigation treatments (Figure 1) and moisture

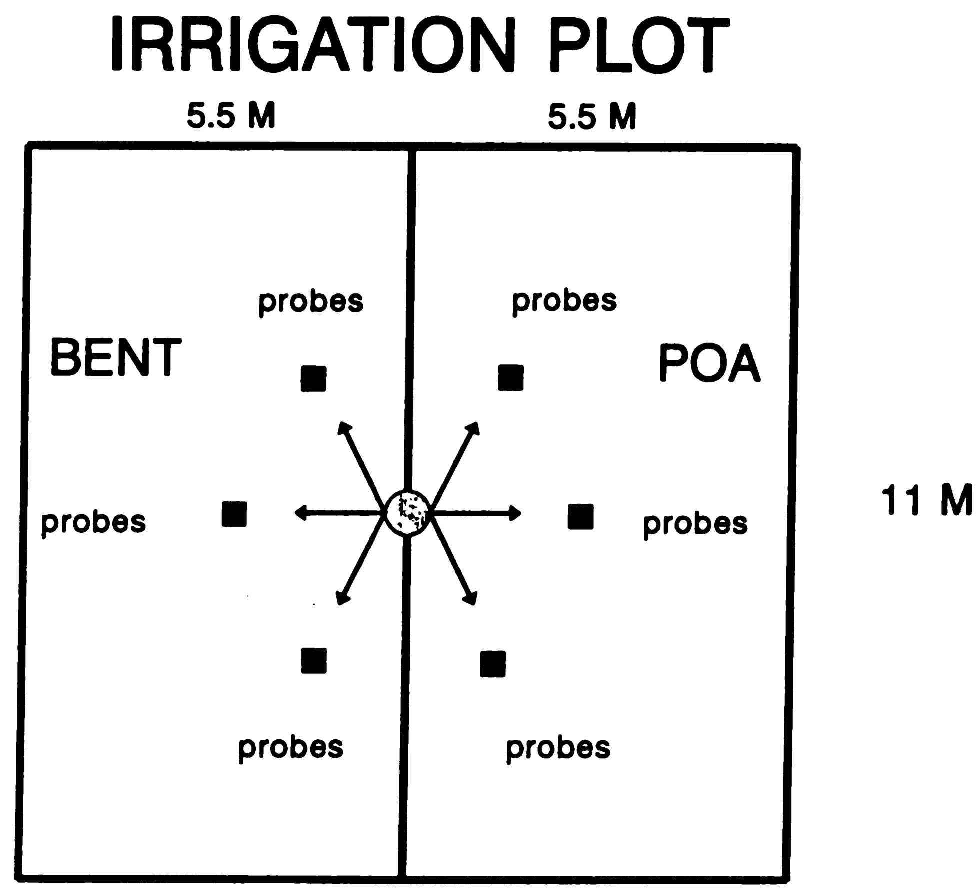

Figure 1. Irrigation Plot Layout

depths split within species.

TDR Installation

The components used in the TDR measurements are a Textronix 1502B cable tester (Textronix Company, Redmond, OR) with serial port, a portable computer with serial port, a serial cable for connecting the cable tester and computer, a coaxial cable supplied with the cable tester, 75-300 ohm balun, dual pole 12 position ceramic switches, Belden 9090 shielded antennae wire, and stainless steel (ER308) welding rod. Another essential part of the system is a computer program that is able to take the information from the cable tester and convert it to volumetric soil moisture. The program is a combination of Textronix TDR communication software, volumetric calculation software from from J.M. Baker, Soil Science Department, University of Minnesota, which was further adapted by workers in the lab of F.J. Pierce, Crop and Soil Science Department, Michigan State University.

In our original testing the connections between the stainless steel wave guides and the antennae wire were soldered and taped. The solder did not hold well to the stainless steel and the connections were not reliable. To correct this holes were drilled in the stainless steel wave guides, and the antennae wire was threaded through the holes and around the wave guides and heavily taped with underground rated electrical tape. These connections proved to be durable with little maintenance required once the system was operative.

Three pairs of wave guides were placed horizontally at depths of 2.5cm, 7.5cm and 12.5cm (Figure 2). These wave guide pairs are placed 5cm apart horizontally, corresponding to the 0-5cm, 5-10cm and 10-15cm depth zones (Topp, 1987). A fourth wave guide pair was installed with one wave guide at 17.5cm and the other at 22.5cm representing the 15-25cm depth zone. The top three wave guide installations were replicated three times per species. The 15-25cm wave guide pair was replicated twice per species. The decision to place the wave guides at these depths is based upon the work of Baker and Lascano (1989). The reason for two replications of the lowest wave guide pair was limited switch positions. The switches have 12 positions, one which must be used by the balun, leaving eleven positions for wave guides. The total number of wave guide pairs in the study was 198.

In the original installation we used phenolic switches as described by Topp (1987). The switches were fitted inside weather proof boxes and placed on posts in the center of the plots. These switches were not durable and warped with temperature change and stress due to the connections of the antennae wire. They were replaced with ceramic switches which proved durable and provided a better connection. Raised center placement of switches also proved undesirable as it disrupted the irrigation pattern and made plot

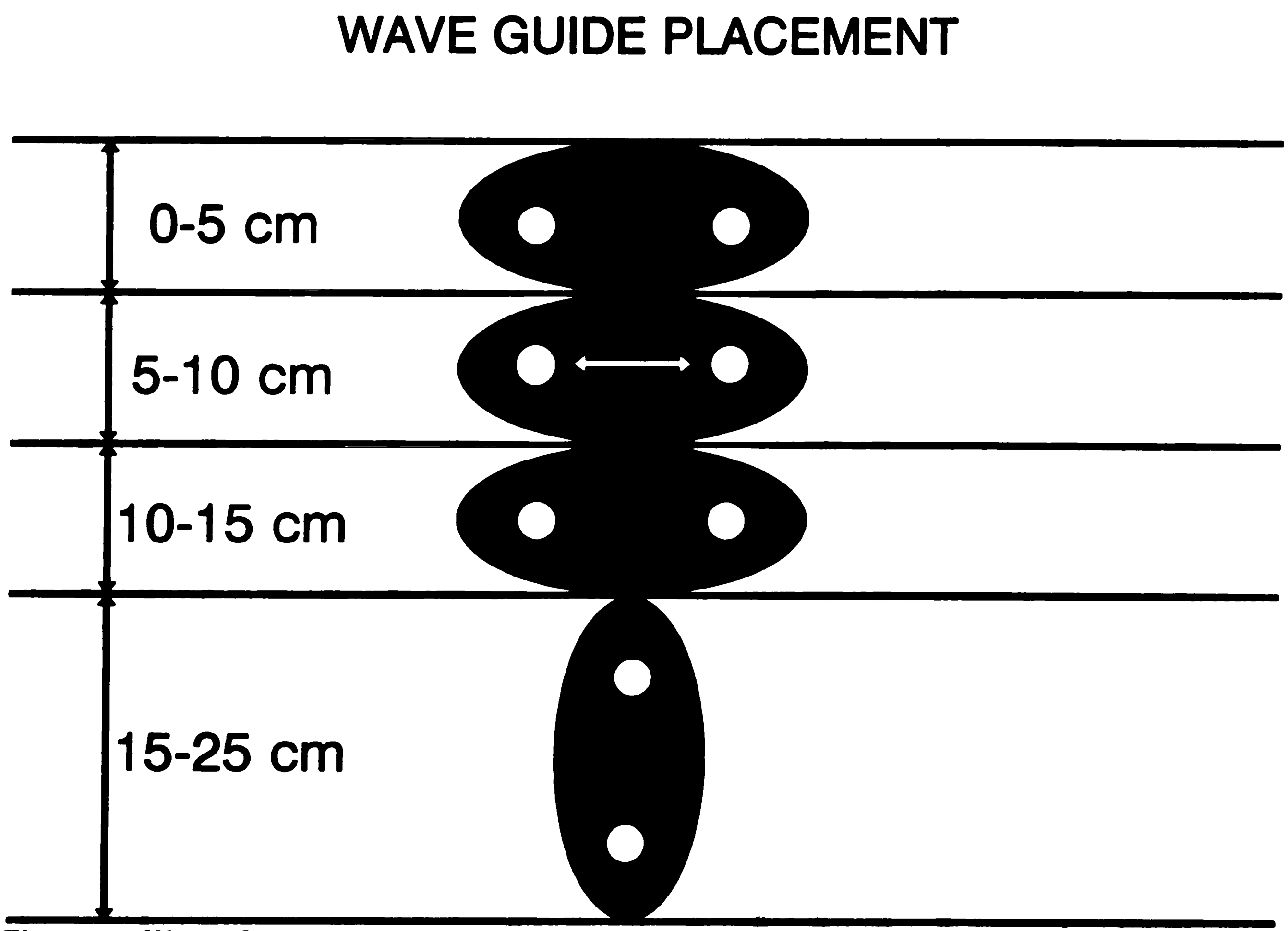

Figure 2. Wave Guide Placement within a Plot

maintenance difficult. The switches were placed underground in valve boxes to correct this problem.

Turfgrass Establishment

The plot area had a mixed population of annual bluegrass and bentgrass. Because of this three applications of 2% glysophate were applied to the plot area during the summer of 1989.

In the summer of 1989 annual bluegrass seed heads were collected, dried and cleaned at the Hancock Turfgrass Research Center at Michigan State University for use in establishing the irrigation plots. This seed was collected from plots originally established in 1980 with seed from annual bluegrass fairways in Mid-Michigan. So it was assumed this seed represents the reptans sub species. It was not possible to get the seed completely clean with the equipment available so the exact seeding rate is not known. The Penncross creeping bentgrass was seeded in the appropriate split plot at a rate of 49 kg ha^{-1}.

With the exception of the irrigation variables, the plots were managed to maintain healthy annual bluegrass fairway turf during the 1991 season. Fertility after establishment was 171 kg ha^{-1} nitrogen per season. Potassium and phosphorus were applied as determined by soil testing. No phosphorus was needed. K_2O was applied at 147 kg ha^{-1} per season in three applications. The annual bluegrass plots received preventative fungicide treatments for summer patch in the summer of 1991. Two applications of triadimefon, June 20 and July 17, 1991, at 6 kg ha^{-1} were applied for summer patch control. No significant disease pressure was observed. Plots were maintained at 1.3cm with clippings removed. Perennial ryegrass (*Lolium perenne* var. Palmer) alleyways of approximately 2.4m wide were established between plots.

Soil Moisture Measurements

Gravimetric soil moisture content was determined by removing three soil cores from each depth in each split plot, weighing, drying at 104° C for 24 hours, weighing after drying and using the weight difference to determine percent moisture by weight. Volumetric soil moisture was determined by multiplying gravimetric soil moisture by soil bulk density (Hillel, 1982). These results were used to compare soil sample volumetric soil moisture data with TDR determined volumetric soil moisture.

Bulk density measurements were made before turfgrass establishment by taking undisturbed samples from the 0-7.6cm, 7.6-15.2cm and 15.2-22.9cm depths. Bulk density was also monitored in the top two zones during the experiment and measured for the TDR measurement depths using 4.5cm by 7.6cm aluminum cylinders to remove undisturbed samples. The surface bulk density decreased to 1.57gcm^{-3} and the 5-10cm zone was 1.60gcm^{-3} at the final measurement (Table 1). The lower zones were also monitored in 7.6cm sections. Bulk density changes in the 0-5cm depth were observed during the study with appropriate changes in volumetric calculations made as needed.

Table 1. Soil Bulk Density grams per cubic centimeter

	Date		
Depth	October 1990	March 1991	July 1991
0-5cm	1.63	1.57	1.57
5-10cm	1.63	1.64	1.60
10-15cm	1.71	1.71	1.71
15-25cm	1.74	1.74	1.74

For each depth and species three subsamples were taken from no nearer than 5 meters from each TDR installation site and combined for one gravimetric sample.

Irrigation Rate and Uniformity Determinations

It was necessary to know the application rate of the irrigation system. Catch cans were placed on a 1.2m grid within the 11m by 11m plot area (100 cans per whole plot). This was done a minimum of three times for each plot for the first evaluation. After the proper sprinkler was selected the irrigation application rate and uniformity was checked periodically throughout the experiment. The original irrigation performance was not uniform and greatly affected by wind. New sprinklers were installed in and spacing corrected. In 1990 several sprinklers were tested with widely different uniformities and application rates. A

12.2m square spacing was found to provide the most uniform coverage. A pressure regulator valve was adjusted to 414 Kpa. Figure 3 shows the uniformity and application rate of the original irrigation installation. Figure 4 shows the uniformity and application of the improved irrigation system, using the sprinkler heads selected during the 1990 testing. The application rate averaged over all plots was 2.03 cm hr^{-1}. As the TDR installation was in the center 37.2m^2 of the plot it was important to know the application rate and uniformity in this area for irrigation scheduling. In the area where TDR measurements were taken the application rate was 2.2 cm hr^{-1}. The field distribution uniformity (derived from catch can data) averaged over all nine plots was 83.1 within the measurement area, and 75% over the entire plot. This was a 20.1% improvement over the previous system in the TDR measurement area and a 44.1% improvement over the whole plot. Irrigation analysis was done on the TURFIMP program developed and supplied by R.L. Snyder, Extension Biometeorologist, Department of Land, Air and Water Resources, University of California at Davis (personal communication).

Calculating Irrigation Needed

TDR volumetric soil moisture determinations were made daily from June 11 to September 11, 1991, except for rain days. The total number of days recorded was 89. Three readings at each of the top three depths for each species

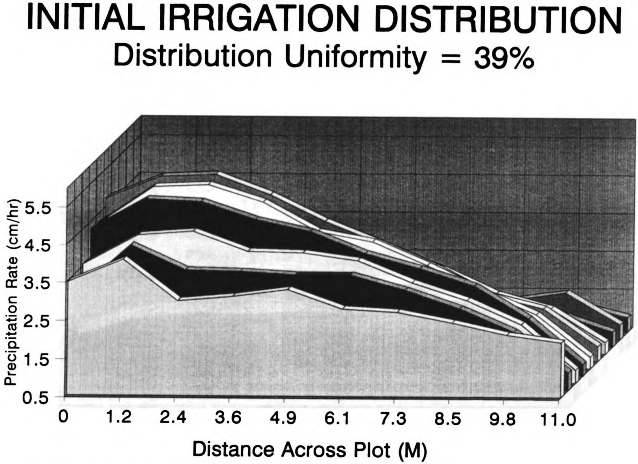

Figure 3. Initial Irrigation Distribution

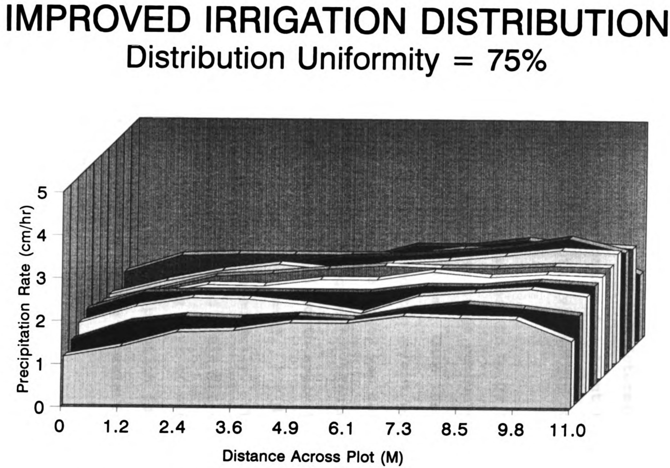

Figure 4. Improved Irrigation Distribution

and treatment were taken. At the lower depth two readings were taken for each species and treatment because of limited switch space. The total number of readings per day was 198. At each depth and for each species and treatment an average soil volumetric moisture content was determined from the the TDR data. Within each irrigation treatment the depths were combined to determine the total volumetric soil moisture in the 0-25cm zone.

Field capacity was determined to be 28.1% volumetric soil moisture. This measurement was conducted in a Soil Moisture pressure device at 300cm. Once the volumetric soil moisture content was determined the amount of water needed to return the plots to field capacity was calculated. The irrigation controller was designed for minutes of irrigation so, the number of minutes required to apply the proper amount was calculated and programmed. Field capacity irrigation amounts were calculated daily. The treatment receiving .25 cm per day required 7 minutes of water daily. Irrigation was not applied during days of significant rain events. Table 2. lists the precipitation for the 1991 testing period. A total of 32.8cm of rain fell during the 1991 testing period.

Table 2. Precipitation Data, cm, for June 11 - September 15, 1991.

June 11	June 15	June 23	July 2	July 4	July 5	July 7
3.5	0.4	3.2	1.4	1.3	0.9	0.8
July 8	July 13	July 21	July 30	Aug 3	Aug 9	Aug 10
1.4	0.2	1.1	3.5	1.4	6.4	0.3
Aug 18	Aug 19	Aug 20	Aug 31	Sept 4	Sept 10	Sept 15
1.6	1.4	0.1	1.9	0.9	0.9	0.2

The plots which were irrigated upon the appearance of stress with the amount of water calcuated to return the soil to field capacity. This treatment was based on wilting of annual bluegrass plots. No water stress was observed in the creeping bentgrass. When wilting of the annual bluegrass plots occurred there was a general pattern of wilting across the entire plot area indicating good uniformity of soil, rooting, and irrigation application. Volumetric soil moisture reading were taken by TDR at 11:00 a.m. and irrigation applications were scheduled for 11:00 pm. to reduce wind effects on application uniformity and to reduce irrigation drift between treatments.

Turfgrass Quality Ratings

Weekly turf quality ratings were taken for each species. Color and turf density were the major determining factors for quality evaluations. Plots were rated on a scale of 1 to 9 with 1 being no turf cover and 9 being excellent turf.

Clipping Weights

Weights were collected weekly from each species within each irrigation plot. A Toro GM1000 mower (Toro Company, Minneapolis, MN) was used to collect samples from an .56m by 5.5m swath through the center each species. Samples were dried at 60 degrees C for 24 hours and weighed.

Turfgrass Root Weights

Root samples from the 0-5cm, 5-10cm, 10-15cm and 15-25cm zones and thatch were collected on July 17 and September 4, 1991. A JMC Backsaver (PN001) with a 3.2cm diameter soil probe (PM013) was used (Clements Associates, Newton, IA). Samples were cleaned of soil with an hydro-pneumatic elutriator (Smucker, et al., 1982), dried and weighed.

RESULTS

TDR EVALUATIONS

TDR vs. Gravimetric Volumetric Soil Moisture

Soil moisture samples were taken on May 2, May 8, June 7, June 10, June 19, July 11, July 26, August 15 and August 23, 1991. In addition to these samples many samples were taken in 1990 during installation and after completion of the TDR system but prior to the beginning of the 1991 trial time.

The gravimetrically derived volumetric soil moisture data was compared by regression analysis to the TDR measured volumetric soil moisture. Each level was analyzed separately in order to determine the accuracy of the measurement in that zone. All data from all levels was combined to determine the degree of agreement between the two methods over the entire 0-25cm profile.

Table 3 contains the regression analyses. The 0-5cm, 5-10cm and 10-15cm zones showed a high degree of correlation between the TDR derived volumetric soil moisture and the soil sample volumetric soil moisture data. The 15-25cm zone does not show as strong a correlation but remains highly significant. A possible reason for this is the larger area measured by this set of wave guides. The area of greatest sensitivity is within 15mm of an individual wave guide and the middle 20mm between the 2 wave guides (Baker and Lascano, 1989). Orienting the wave guides one above the other likely measured the area between the wave guides but was not representative of the entire 15-25cm zone.

Table 3. Correlation Data, TDR vs. Soil Sample

ZONE	CORRELATION	SLOPE
0-5cm	.898***	1.001
5-10cm	.879***	0.929
10-15cm	.847***	0.926
15-25cm	.828***	1.081
0-25cm	.854***	0.880

The data is shown graphically in Figures 5, 6, 7, 8 and 9. These graphs show the high degree of correlation between the two methods. With high correlations, slopes near one, and the number of samples taken the TDR technique provides accuracy and speed in volumetric soil moisture measurements.

Each TDR measurement required approximately 8 seconds and was not destructive to the plot. In gravimetric sampling many holes are made in the plot. These holes could affect water movement and other physical properties of the soil. Each soil sample requires physical removal of a sample, weighing, 24 hours to dry, weighing and calculation to obtain a volumetric soil moisture content. Not only was this time consuming, but would not be adequate for making decisions on amounts of irrigation needed for a given day.

Irrigation Application

Volumetric soil moisture as determined by TDR was measured each day and irrigation scheduled at 12:00 p.m. except when significant rainfall occurred. The TDR equipment would have been damaged by moisture and thus readings could not be taken in the rain. Sixty-six TDR measurements were taken from each treatment for the four depths. Data was averaged for each depth and combined over the profile to determine the volumetric soil moisture. This was used to determine how much water would be needed to bring the soil back to field capacity for the field capacity and stress based treatments. For the .25cm daily treatment soil moisture contents were also recorded. Table 4 shows the total amount of irrigation applied for each treatment during the 1991 study period.

Table 4. Total Irrigation Applied, June 11 - September 11, 1991

Treatment	Total Irrigation Amount
Field Capacity	25.3cm
.25cm per day	19.8cm
Irrigation at Wilt	7.8cm

The field capacity plots were irrigated back to field capacity whenever they were below field capacity. The irrigation amounts varied daily in the field capacity plots, however the volumetric soil moisture content did not. Figure 10 graphs irrigation amounts applied to the field capacity treatment and volumetric soil moisture, as well as a line indicating field capacity. This graph illustrates that by using the TDR method and knowing the application rate of the irrigation system one can determine the irrigation amount needed to return the soil to a desired moisture content. The field capacity measurements averaged 1.1% below field capacity because the readings were taken prior to irrigation.

Figure 11 shows the same data for the .25cm daily treatment. This irrigation schedule did not keep up with water loss from the soil during periods of several days with no precipitation. There was a gradual lowering of the volumetric soil moisture during these periods with slight wilting than did not result in long term quality reduction.

The stress treatment was irrigated only three times in 1991, June 20, July 15 and July 28. Stress was determined visually and by foot printing of the annual bluegrass. Figure 12 shows the wide variation in soil moisture content over the season. It also shows that a single irrigation based upon TDR data did not bring the soil back to field capacity.

Soil Moisture Evaluations

The soil moisture data was analyzed as a split-split plot design. This design allows for 12 comparisons. Of the twelve, four were found to be significant: irrigation treatment effects, moisture content changes by depth, differences among irrigation treatments at the same depth and differences among depths at the same irrigation. Statistical analysis of was conducted using MSTATC 4.0 statistical package (MSTAT Development Team, 1990).

Irrigation Treatments Main Effects

Split-split plot designs do not have a high degree of precision for the whole plots. Because of this and consistent irrigation treatment by depth interactions, significant irrigation treatment differences could only be found for 14 of the 89 treatment dates. Table 5 gives the moisture data in the 0-25cm profile for days in 1991 when there were significant differences in irrigation effects. It should be noted that there were consistent significant F tests for irrigation differences, however irrigation treatment by depth interactions precluded examining the data further.

Significant differences in volumetric soil moisture content were found between the field capacity and stress treatments on 9 of 14 dates. The .25cm daily treatment had less water than the field capacity treatment on three dates, July 2, 21 and 24. On July 2 and 24 there was no difference in soil moisture between the stress and .25cm treatments. On nine dates the .25cm treatment had more water than the stress treatment, while on July 21 there was more water in the stress treatment. Figure 14 charts the soil profile moisture content of the irrigation treatments for the 1991 season for the three irrigation regimes.

On four dates the field capacity treatment exceeded field capacity. The August 19 and 20 dates were preceded by 1.6cm of rain on August 18 and 1.4cm on the 19th. The reading exceeding field capacity for the fourth of September was due to .9cm rain on September 4. The September 10 measurement was preceded by .9cm rain. No irrigation was applied to the field capacity plots on any of these dates. The .25cm daily treatment also exceeded field capacity on these dates, however the excess moisture was partly from the irrigation received on those dates. Because of this it should be clear that the TDR scheduled irrigation was not the cause excess moisture.

Table 5. Irrigation Treatment Volumetric Soil Moisture Effects in 0-25cm Profile, 1991

Irrigation Treatment	Date						
	7/2	7/21	7/24	8/4	8/5	8/11	8/12
Field Capacity	27.8	27.9	26.6	27.9	26.9	28.0	26.2
.25cm Daily	22.4	21.6	21.8	26.9	26.2	27.8	26.5
Stress Only	24.9	27.0	24.3	24.9	23.4	26.2	24.3
LSD P=.05	3.05	3.77	3.67	2.67	2.74	2.12	2.10

Table 5. Irrigation Treatment Volumetric Soil Moisture Effects in 0-25cm Profile, 1991, continued

Irrigation Treatment	Date						
	8/19	8/20	8/21	8/22	9/4	9/5	9/10
Field Capacity	30.0	29.3	27.8	27.1	29.2	27.7	29.3
.25cm Daily	29.2	28.4	27.7	27.1	28.8	27.8	28.9
Stress Only	26.6	25.9	24.6	23.4	26.2	24.8	23.1
LSD P=.05	2.27	1.94	2.47	2.61	2.07	2.08	1.86

Moisture Differences by Depth over all Treatments

Table 6 gives the soil moisture content by depth across all irrigation treatments on dates when significant differences occurred in 1991. There were 42 days during the 89 day study period which had significant differences in the volumetric moisture content among depths. The overall tendency was for moisture to decrease with depth. For only two dates, July 21 and August 5, there were no difference between the 0-5cm and 5-10cm depths, the first date the stress treatment was irrigated and the second was rain affected. On 22 dates the 5-10 and 10-15cm depths were not significantly different, while on the remaining 20 dates the 5-10cm depth had higher moisture contents. Three dates showed no significant difference among the lowest three depths. The lowest two depths were not significantly different for 13 dates. Figure 15 displays the 1991 season volumetric soil moisture by depth over all treatments.

Table 6. Volumetric Soil Moisture Content Differences by Depth Across all Treatments, 1991.

Depth	Date						
	6/11	6/12	6/13	6/23	6/24	6/25	6/26
0-5cm	30.9	28.6	26.1	29.2	26.6	26.6	25.6
5-10cm	28.2	26.8	24.7	27.6	25.6	25.0	24.1
10-15cm	26.6	25.8	24.1	26.8	25.4	24.8	24.1
15-25cm	24.3	23.9	23.3	25.3	24.4	24.0	23.6
LSD P=.05	0.79	0.78	0.69	0.64	0.66	0.65	0.70

Table 6. Volumetric Soil Moisture Content Differences by Depth Across all Treatments, 1991, continued.

Depth	Date						
	7/2	7/3	7/4	7/5	7/6	7/7	7/8
0-5cm	28.0	25.7	30.7	29.0	26.7	28.5	29.9
5-10cm	25.4	24.1	28.8	27.3	25.6	26.5	28.3
10-15cm	23.7	23.3	27.5	26.6	25.4	25.6	27.5
15-25cm	23.0	22.2	26.1	25.0	24.4	24.2	26.3
LSD P=.05	1.05	1.18	0.76	0.76	0.76	0.79	0.75

Table 6. Volumetric Soil Moisture Content Differences by Depth Across all Treatments, 1991, continued.

Depth	Date						
	7/9	7/10	7/11	7/17	7/21	7/23	7/24
0-5cm	27.5	26.2	25.9	26.2	25.6	27.5	25.2
5-10cm	26.6	25.3	24.8	24.7	26.0	25.5	24.3
10-15cm	26.3	25.2	24.7	24.1	24.6	24.8	24.1
15-25cm	25.3	24.6	24.2	23.1	23.0	23.7	23.3
LSD P=.05	0.75	0.82	0.84	0.81	0.83	1.73	0.71

Table 6. Volumetric Soil Moisture Content Differences by Depth Across all Treatments, 1991, continued.

Depth	Date						
	7/30	7/31	8/1	8/3	8/4	8/5	8/10
0-5cm	30.4	28.2	26.5	29.7	28.2	26.5	29.7
5-10cm	28.5	27.1	25.7	27.6	26.9	25.7	28.1
10-15cm	27.4	26.4	25.5	26.6	26.1	25.3	27.2
15-25cm	26.1	25.3	24.8	25.4	25.2	24.6	26.3
LSD P=.05	0.67	0.77	0.79	0.75	0.75	0.81	0.72

Table 6. Volumetric Soil Moisture Content Differences by Depth Across all Treatments, 1991, continued.

Depth	Date						
	8/11	8/12	8/19	8/20	8/21	8/22	8/27
0-5cm	29.1	26.4	31.5	30.2	28.2	27.2	28.1
5-10cm	27.5	25.6	29.1	28.1	26.8	25.8	25.9
10-15cm	26.8	25.6	27.7	27.2	26.4	25.7	25.0
15-25cm	25.8	25.1	26.2	26.0	25.4	24.9	23.9
LSD P=.05	0.72	0.76	0.72	0.72	0.76	0.79	0.79

Table 6. Volumetic Soil Moisture Content Differences by Depth Across all Treatments, 1991, continued

Depth	Date						
	8/28	8/31	9/1	9/4	9/5	9/10	9/11
0-5cm	27.3	30.4	28.8	31.0	28.8	30.0	31.2
5-10cm	25.2	27.9	27.1	28.4	26.8	27.1	28.6
10-15cm	24.5	27.1	26.4	27.1	26.1	26.0	27.6
15-25cm	23.6	26.7	25.7	25.8	25.5	25.4	26.3
LSD P=.05	0.78	0.67	0.80	0.77	0.82	0.82	1.00

Soil Moisture by Depth within Field Capacity Irrigation Treatment

The greatest number of significant differences in soil moisture occurred with the interaction between irrigation treatment and depth. This allows the evaluation of the soil moisture changes with depth within an irrigation treatment, as well as evaluation of differences among irrigation treatments at the same depth.

Table 7 lists the volumetric soil moisture by depth within the field capacity treatment. There were 46 dates when significant differences occurred. The surface 5cm had significantly greater volumetric soil moisture content compared to other depths. On only 2 of the 46 dates, June 15 and August 9, was the 5-10cm depth moisture content higher than in the 10-15cm depth. On 38 dates there was no difference between the 10-15cm and 15-25cm depths. Figure 16 tracks the mean volumetric soil moisture content by depth within the field capacity treatment.

Table 7. Volumetric Soil Moisture Content by Depth, Field Capacity Treatment, 1991.

Field Capacity	Date						
Depth	6/14	6/15	6/16	6/17	6/18	6/19	6/20
0-5cm	26.9	29.4	28.5	28.0	27.6	27.2	29.0
5-10cm	25.4	27.0	26.5	25.9	25.6	25.4	26.2
10-15cm	24.6	25.7	25.5	25.2	24.8	24.6	25.0
15-25cm	23.0	23.6	24.0	23.8	23.7	23.6	23.3
LSD P=.05	1.19	1.19	1.40	1.42	1.23	1.35	1.51

Table 7. Volumetric Soil Moisture Content by Depth, Field Capacity Treatment, 1991, continued.

Field Capacity	Date						
Depth	6/21	6/27	6/28	6/29	6/30	7/1	7/12
0-5cm	28.1	26.3	27.3	27.8	27.9	29.2	27.4
5-10cm	26.1	24.9	25.4	25.8	25.8	26.3	25.6
10-15cm	24.8	24.8	24.9	24.9	24.9	24.9	25.2
15-25cm	22.7	24.6	24.3	24.4	24.0	24.0	24.4
LSD P=.05	1.56	1.28	1.28	1.35	1.21	1.87	1.39

Table 7. Volumetric Soil Moisture Content by Depth, Field Capacity Treatment, 1991, continued.

Field Capacity	Date						
Depth	7/13	7/14	7/15	7/16	7/18	7/19	7/20
0-5cm	31.3	30.5	28.1	29.0	29.2	29.3	28.9
5-10cm	27.9	27.8	26.4	26.6	26.5	26.6	26.3
10-15cm	26.7	26.7	25.9	26.0	25.8	25.9	25.6
15-25cm	25.1	25.3	25.1	24.8	24.7	24.8	24.7
LSD P=.05	1.52	1.34	1.48	1.41	1.36	1.40	1.45

Table 7. Volumetric Soil Moisture Content by Depth, Field Capacity Treatment, 1991, continued.

Field Capacity	Date						
Depth	7/22	7/25	7/26	7/27	7/28	8/2	8/6
0-5cm	32.8	28.1	29.2	29.0	29.7	28.2	28.4
5-10cm	30.2	26.0	25.6	26.6	27.0	26.1	26.5
10-15cm	30.7	25.7	26.0	26.0	26.1	25.9	26.1
15-25cm	27.5	25.1	25.0	25.1	25.0	25.2	25.6
LSD P=.05	1.61	1.32	1.33	1.41	1.46	1.50	1.34

Table 7. Volumetric Soil Moisture Content by Depth, Field Capacity Treatment, 1991, continued.

Field Capacity	Date						
Depth	8/7	8/9	8/13	8/14	8/15	8/16	8/17
0-5cm	28.1	33.4	29.3	28.8	30.3	28.1	32.3
5-10cm	26.0	30.4	27.0	26.6	27.3	26.0	29.6
10-15cm	25.6	28.9	26.3	25.9	26.4	25.9	28.6
15-25cm	24.9	29.9	25.7	25.4	25.5	25.1	27.8
LSD P=.05	1.37	1.02	1.35	1.53	1.55	1.73	1.43

Table 7. Volumetric Soil Moisture Content by Depth, Field Capacity Treatment, 1991, continued.

Field Capacity	Date						
Depth	8/23	8/24	8/25	8/26	8/29	9/2	9/3
0-5cm	28.3	28.7	29.4	30.2	30.3	28.9	29.2
5-10cm	26.4	26.4	26.4	26.9	27.0	26.7	26.6
10-15cm	26.3	26.0	25.9	26.2	26.1	26.3	26.2
15-25cm	25.7	25.5	25.2	25.2	25.1	25.8	25.5
LSD P=.05	1.41	1.45	1.53	1.54	1.38	1.32	1.39

Table 7. Volumetric Soil Moisture Content by Depth, Field Capacity Treatment, 1991, continued.

Field Capacity	Date			
Depth	9/6	9/7	9/8	9/9
0-5cm	29.5	28.8	30.3	30.3
5-10cm	27.0	26.4	27.1	27.0
10-15cm	26.9	26.3	26.4	26.3
15-25cm	25.9	25.4	25.4	25.5
LSD P=.05	1.31	1.38	1.49	1.49

Soil Moisture by Depth within .25cm Daily Irrigation Treatment

The .25cm daily treatment (Table 8) had 44 dates when there were significant differences in volumetric soil moisture. Again the trend is for decreasing moisture with increased depth, as shown in Figure 17. However the differences are not a clear as in the field capacity treatment. On 33 dates the surface moisture content was significantly greater than the other levels. For 42 dates there were no differences between the 5-10cm and 10-15cm depths. There was only 1 date with a difference between the 10-15cm and 15-25cm depths. There were 11 dates where the 5-10cm depth moisture content exceeded the 15-25cm depth moisture content. For 10 dates the 0-5cm depth exceeded field capacity. The 5-10cm depth was greater than field capacity on two dates.

Table 8. Volumetric Soil Moisture Content by depth, .25cm Daily Treatment, 1991.

.25cm	Date						
Depth	6/14	6/15	6/16	6/17	6/18	6/19	6/20
0-5cm	25.1	25.7	24.9	24.3	23.0	22.4	21.9
5-10cm	23.4	23.3	22.9	22.2	21.3	20.8	20.5
10-15cm	23.2	22.6	22.4	21.6	20.7	20.4	19.5
15-25cm	22.7	22.3	21.8	21.3	20.6	20.1	19.7
LSD P=.05	1.19	1.19	1.40	1.42	1.23	1.35	1.51

Table 8. Volumetric Soil Moisture Content by depth, .25cm Daily Treatment, 1991, continued.

.25cm	Date						
Depth	6/21	6/27	6/28	6/29	6/30	7/12	7/13
0-5cm	31.3	24.9	23.4	22.7	21.9	26.0	27.4
5-10cm	20.0	23.3	22.4	21.6	21.0	24.3	25.0
10-15cm	18.9	23.2	22.0	21.1	20.7	24.4	24.6
15-25cm	19.4	22.7	21.8	20.8	20.6	23.7	23.6
LSD P=.05	1.56	1.28	1.28	1.35	1.21	1.39	1.52

Table 8. Volumetric Soil Moisture Content by depth, .25cm Daily Treatment, 1991, continued.

.25cm	Date						
Depth	7/14	7/15	7/16	7/18	7/19	7/20	7/22
0-5cm	28.0	26.3	25.7	24.0	23.2	22.2	28.8
5-10cm	25.2	24.2	23.8	22.5	22.6	21.0	24.4
10-15cm	24.8	24.1	23.6	22.2	21.7	21.0	22.2
15-25cm	23.7	23.2	22.8	21.6	21.2	20.6	20.6
LSD P=.05	1.34	1.48	1.41	1.36	1.40	1.45	1.61

Table 8. Volumetric Soil Moisture Content by depth, .25cm Daily Treatment, 1991, continued.

.25cm	Date						
Depth	7/25	7/26	7/27	8/2	8/6	8/7	8/9
0-5cm	21.7	21.4	21.0	25.6	26.8	25.7	31.4
5-10cm	20.8	20.4	20.1	24.7	25.6	24.4	29.0
10-15cm	20.6	20.2	20.0	24.6	25.4	24.4	27.8
15-25cm	20.2	19.8	19.5	23.8	24.4	23.8	26.9
LSD P=.05	1.32	1.33	1.41	1.50	1.34	1.37	1.02

Table 8. Volumetric Soil Moisture Content by depth, .25cm Daily Treatment, 1991, continued.

.25cm	Date						
Depth	8/13	8/14	8/16	8/16	8/17	8/23	8/24
0-5cm	27.9	27.1	26.7	25.8	31.2	28.4	27.8
5-10cm	26.4	25.6	25.1	24.2	28.4	26.3	25.7
10-15cm	26.1	25.5	25.1	24.2	27.0	26.2	25.6
15-25cm	25.0	24.4	24.2	23.6	25.2	25.2	24.8
LSD P=.05	1.35	1.53	1.55	1.73	1.43	1.41	1.45

Table 8. Volumetric Soil Moisture Content by depth, .25cm Daily Treatment, 1991, continued.

.25cm	Date						
Depth	8/25	8/26	8/29	9/2	9/3	9/6	9/7
0-5cm	27.4	27.1	26.4	29.1	28.2	30.4	29.2
5-10cm	25.2	24.9	23.9	26.8	26.3	27.6	26.8
10-15cm	25.0	24.5	23.4	26.1	25.7	26.8	26.3
15-25cm	24.2	23.8	22.7	25.2	24.8	25.6	25.0
LSD P=.05	1.53	1.54	1.38	1.32	1.39	1.31	1.38

Table 8. Volumetric Soil Moisture Content by depth, .25cm Daily Treatment, 1991, continued.

.25cm	Date	
Depth	9/8	9/9
0-5cm	29.6	29.4
5-10cm	26.8	26.6
10-15cm	26.0	25.8
15-25cm	24.8	24.6
LSD P=.05	1.49	1.49

Soil Moisture by Depth within Stress Irrigation Treatment

The soil moisture contents depth for the stress irrigation treatment (Table 9) were largely affected by rain. The moisture distribution during drying periods was driest in the 0-5cm depth with increasing moisture with increased depth. After a rain or one of the three irrigation events during the year the trend reversed for a few days. There were 26 dates with significant differences in volumetric soil moisture content; 5 dates when 0-5cm depth exceeded 5-10cm depth; 14 dates when 5-10cm depth was higher than the 0-5cm depth; 5 when 10-15cm depth was less than 5-10cm depth; 6 when 10-15cm depth exceeded 15-25cm depth; 15 dates when 10-15cm depth exceeded 0-5cm and 5 dates when 0-5cm depth exceeded 10-15cm depth. In general, the upper layers were greater than the lower layers only after irrigation or rainfall. Figure 18 shows this trend. There were 3 dates where the 0-5cm depth exceeded field capacity. Two dates were associated with rain and one date following one of the three irrigations.

Table 9. Volumetric Soil Moisture Content by Depth, Stress Treatment, 1991.

Stress	Date						
Depth	6/18	6/19	6/20	6/21	6/28	6/29	6/30
0-5cm	15.8	14.5	13.6	29.0	17.9	16.0	27.9
5-10cm	17.9	16.8	16.2	25.9	19.4	17.9	26.3
10-15cm	18.3	17.7	17.1	22.4	19.9	18.8	24.8
15-25cm	18.1	17.5	17.1	19.1	19.9	18.7	21.8
LSD P=.05	1.23	1.35	1.51	1.56	1.28	1.21	1.21

Table 9. Volumetric Soil Moisture Content by Depth, Stress Treatment, 1991, continued.

Stress	Date						
Depth	7/1	7/15	7/16	7/18	7/20	7/22	7/26
0-5cm	25.4	19.3	28.2	22.4	17.5	31.6	19.5
5-10cm	24.7	21.0	26.7	22.9	19.7	29.7	21.1
10-15cm	24.0	20.7	24.7	22.4	19.6	27.6	21.1
15-25cm	21.8	20.5	22.2	21.3	20.0	25.2	21.2
LSD P=.05	1.87	1.48	1.41	1.36	1.45	1.61	1.33

Table 9. Volumetric Soil Moisture Content by Depth, Stress Treatment, 1991, continued.

Stress	Date						
Depth	7/27	7/28	8/2	8/7	8/9	8/14	8/15
0-5cm	17.4	16.6	21.7	19.4	31.2	21.1	19.9
5-10cm	20.2	19.4	22.9	21.0	29.2	22.1	21.5
10-15cm	20.0	19.4	23.1	21.1	27.8	22.5	21.8
15-25cm	20.4	19.6	23.4	21.3	25.8	22.7	21.9
LSD P=.05	1.41	1.46	1.50	1.37	1.02	1.53	1.55

Table 9. Volumetric Soil Moisture Content by Depth, Stress Treatment, 1991, continued.

Stress	Date				
Depth	8/16	8/24	8/25	8/26	8/29
0-5cm	18.2	20.5	19.0	17.6	24.2
5-10cm	20.1	21.0	20.2	19.2	23.5
10-15cm	20.7	21.7	20.7	20.0	23.1
15-25cm	20.2	22.0	20.8	20.1	22.6
LSD P=.05	1.73	1.45	1.53	1.54	1.38

Soil Moisture Differences for the 0-5cm Depth Across Treatments

Another comparison that can be made in the irrigation treatment by depth interaction is for the three irrigation treatments at the same depth.

There were 45 dates with differences. The 0-5cm depth volumetric moisture content in the field capacity plots was never less than for the .25cm daily or stress treatments. On 24 dates field capacity had greater moisture than the .25cm daily treatment and 35 dates when .25cm daily volumetric soil moisture was greater than for the stress treatment. For 3 dates the stress treatment exceeded the .25cm treatment, all following rain or irrigation. For 7 dates there was no difference between the .25cm daily and stress treatments. Of the 45 dates with significant differences, the field capacity treatment exceeded field capacity, 28.1%, on 31 dates, 9 dates for .25cm daily treatment and 3 dates for the stress treatment. For several days after a rain there were no differences, followed by dates with differences and continued higher than field capacity readings in the 0-5cm depth in the field capacity treatment. For the .25cm daily treatment 3 of the dates when soil moisture exceeded field capacity were rainfall events. The other 5 dates follow the same pattern as the field capacity treatment of continued high 0-5cm readings several days after rainfall. All 3 dates where the volumetric soil moisture content in the 0-5cm depth in the stress treatment exceeded field capacity were associated with rain. Table 10 lists the data and Figure 19 charts the soil moisture changes.

Table 10. Volumetric Soil Moisture Content for Irrigation Treatments at the 0-5cm Depth, 1991.

	Date						
Treatment	6/14	6/15	6/16	6/17	6/18	6/19	6/20
Field Capacity	26.9	29.4	28.5	28.0	27.6	27.2	29.0
.25cm Daily	25.1	25.7	24.9	24.3	23.0	22.3	21.9
Stress	20.9	20.4	19.7	18.4	15.8	14.5	13.6
LSD P=.05	2.22	2.29	2.28	2.65	2.60	2.86	3.14

Table 10. Volumetric Soil Moisture Content for Irrigation Treatments at the 0-5cm Depth, 1991, continued.

	Date						
Treatment	6/21	6/27	6/28	6/29	6/30	7/1	7/12
Field Capacity	28.1	26.3	27.3	27.8	27.9	29.2	27.4
.25cm Daily	21.3	24.9	23.4	22.7	21.9	21.6	26.0
Stress	29.0	20.0	17.9	16.0	27.9	25.4	21.7
LSD P=.05	2.79	2.96	2.96	3.51	2.80	2.75	3.57

Table 10. Volumetric Soil Moisture Content for Irrigation Treatments at the 0-5cm Depth, 1991, continued.

Irrigation Treatment	Date						
	7/13	7/14	7/15	7/16	7/18	7/19	7/20
Field Capacity	31.3	30.5	28.1	29.0	29.2	29.3	28.9
.25cm Daily	27.4	28.0	26.3	25.7	24.0	23.2	22.2
Stress	21.8	21.8	19.3	28.2	22.4	19.9	17.5
LSD P=.05	3.52	3.35	3.55	3.28	3.50	4.19	3.72

Table 10. Volumetric Soil Moisture Content for Irrigation Treatments at the 0-5cm Depth, 1991, continued.

Irrigation Treatments	Date						
	7/25	7/26	7/27	7/28	8/2	8/6	8/7
Field Capacity	28.1	29.2	29.0	29.7	28.2	28.4	28.1
.25cm Daily	21.7	21.4	21.0	20.7	25.6	26.0	25.7
Stress	21.4	19.5	17.4	16.6	21.7	21.7	19.4
LSD P=.05	3.5	3.11	3.38	3.72	2.91	2.72	2.79

Table 10. Volumetric Soil Moisture Content for Irrigation Treatments at the 0-5cm Depth, 1991, continued.

Irrigation Treatments	Date						
	8/9	8/13	8/14	8/15	8/16	8/17	8/23
Field Capacity	33.4	29.3	28.8	30.3	28.1	32.3	28.3
.25cm Daily	31.4	27.9	27.1	26.7	25.8	31.2	28.4
Stress	31.2	23.0	21.1	19.9	18.1	22.6	21.6
LSD P=.05	1.84	2.09	2.02	2.20	2.65	2.56	2.09

Table 10. Volumetric Soil Moisture Content for Irrigation Treatments at the 0-5cm Depth, 1991, continued.

Irrigation Treatment	Date						
	8/24	8/25	8/26	8/29	9/2	9/3	9/6
Field Capacity	28.7	29.4	30.2	30.3	28.9	29.2	29.5
.25cm Daily	27.8	27.4	27.1	26.4	29.1	28.2	30.4
Stress	20.5	19.0	17.6	24.1	24.7	22.9	24.4
LSD P=.05	2.15	2.38	2.83	2.31	2.05	2.18	2.22

Table 10. Volumetric Soil Moisture Content for Irrigation Treatments at the 0-5cm Depth, 1991, continued.

Irrigation Treatment	Date		
	9/7	9/8	9/9
Field Capacity	28.8	30.3	30.3
.25cm Daily	29.2	29.6	29.4
Stress	22.3	21.6	20.5
LSD P=.05	2.09	2.16	2.18

Soil Moisture Differences for the 5-10cm Depth Across Treatments

In the 5-10cm depth (Table 11) the irrigation season started with 11 of the 13 dates where the field capacity treatment had higher moisture than the .25cm daily plots. By the middle of August the trend changed to field capacity and .25cm daily treatments having equal moisture and both were greater than for the stress treatment. Figure 20 shows a graph of the soil moisture content at the 5-10cm depth. On many dates there was greater volumetric soil moisture in the .25cm daily plots than for the stress plots as would be expected, while on five dates earlier in the season the stress irrigated plots had more moisture than the .25cm daily plots. The dynamic nature of the shifts in the 5-10cm depth between .25cm daily and stress irrigation reflects the timing of irrigation and rainfall events. An example would be the lower moisture content for the stress treatment on June 28 and 29 followed by higher moisture on June 30 and July 1 following the stress irrigation on June 29. At this depth there were 3 dates when field capacity was exceeded in the field capacity plots, all three were due to rainfall. One date exceeded field capacity in the .25cm daily treatment, August 17, due to rainfall. The 5-10cm depth stress treatment did not exceed field capacity.

Table 11. Volumetric Soil Moisture Content for Irrigation Treatments at the 5-10 Depth, 1991.

Irrigation Treatments	Date						
	6/14	6/15	6/16	6/17	6/18	6/19	6/20
Field Capacity	25.4	27.0	26.6	25.9	25.6	25.4	26.2
.25cm Daily	23.4	23.3	22.9	22.2	21.3	20.8	20.5
Stress	21.5	20.8	20.5	19.4	17.9	16.8	16.2
LSD P=.05	2.22	2.29	2.28	2.65	2.60	2.86	3.14

Table 11. Volumetric Soil Moisture Content for Irrigation Treatments at the 5-10 Depth, 1991, continued.

Irrigation Treatments	Date						
	6/21	6/27	6/28	6/29	6/30	7/1	7/12
Field Capacity	26.1	24.9	25.4	25.8	25.8	26.3	25.6
.25cm Daily	20.0	23.3	22.4	21.6	21.0	21.0	24.3
Stress	25.9	20.6	19.4	17.9	26.3	24.7	21.9
LSD P=.05	2.79	2.96	2.96	3.51	2.80	2.75	3.57

Table 11. Volumetric Soil Moisture Content for Irrigation Treatments at the 5-10 Depth, 1991, continued.

Irrigation Treatments	Date					
	7/13	7/14	7/15	7/18	7/19	7/20
Field Capacity	27.9	27.8	26.4	26.5	26.6	26.3
.25cm Daily	25.0	25.2	24.2	22.5	22.6	21.0
Stress	22.2	22.3	21.0	22.9	21.2	19.7
LSD P=.05	3.52	3.35	3.55	3.50	4.19	3.72

Table 11. Volumetric Soil Moisture Content for Irrigation Treatments at the 5-10 Depth, 1991, continued.

Irrigation Treatments	Date						
	7/22	7/25	7/26	7/27	7/28	8/2	8/6
Field Capacity	30.2	26.0	26.6	26.6	27.0	26.1	26.5
.25cm Daily	24.4	20.8	20.4	20.1	20.0	24.7	25.6
Stress	29.7	22.7	21.1	20.0	19.4	22.9	22.3
LSD P=.05	4.23	3.50	3.11	3.38	3.72	2.91	2.72

Table 11. Volumetric Soil Moisture Content for Irrigation Treatments at the 5-10 Depth, 1991, continued.

Irrigation Treatments	Date						
	8/7	8/9	8/13	8/14	8/15	8/16	8/17
Field Capacity	26.0	30.4	27.0	26.6	27.3	26.0	29.6
.25cm Daily	24.4	26.0	26.4	25.6	25.1	24.2	28.4
Stress	21.0	29.2	23.4	22.1	21.5	20.1	22.9
LSD P=.05	2.79	1.84	2.09	2.02	2.20	2.65	2.56

Table 11. Volumetric Soil Moisture Content for Irrigation Treatments at the 5-10 Depth, 1991, continued.

Irrigation Treatments	Date						
	8/23	8/24	8/25	8/26	8/29	9/2	9/3
Field Capacity	26.4	26.4	26.4	26.9	27.0	26.7	26.6
.25cm Daily	26.3	25.7	25.2	24.9	23.9	26.8	26.3
Stress	21.6	21.0	20.2	19.2	23.5	24.4	22.9
LSD P=.05	2.09	2.15	2.38	2.83	2.31	2.05	2.18

Table 11. Volumetric Soil Moisture Content for Irrigation Treatments at the 5-10 Depth, 1991, continued.

Irrigation Treatment	Date			
	9/6	9/7	9/8	9/9
Field Capacity	27.0	26.4	27.1	27.0
.25cm Daily	27.6	26.8	26.8	26.6
Stress	23.8	22.4	21.9	21.0
LSD P=.05	2.22	2.09	2.16	2.18

<u>Soil Moisture Differences for the 10-15cm Depth Across Treatments</u>

Again the trend is for the field capacity treatment to have the highest soil moisture, followed by the stress treatment and the stress treatment with the lowest soil moisture. The 10-15cm depth had 41 dates with significant differences. For 19 dates the field capacity had greater moisture then the .25cm daily treatment and for all but 6 dates field capacity was greater than the stress treatment. On those 6 dates where field capacity was not greater than stress, 3 were related to irrigation events and 3 related to rain. The .25cm daily treatment had higher moisture than the stress treatment on 18 dates. Stress was greater than .25cm daily on 3 dates, 2 caused irrigation and 1 by rain. Three dates exceeded field capacity in the field capacity treatment, all resulting from rainfall. This data is listed in Table 12 and reflected in Figure 21.

Table 12. Volumetric Soil Moisture Content for Irrigation Treatments at the 10-15cm Depth, 1991.

Irrigation Treatments	Date						
	6/14	6/15	6/16	6/17	6/18	6/19	6/20
Field Capacity	24.6	25.7	25.5	25.2	24.8	24.6	25.0
.25cm Daily	23.2	22.7	22.4	21.6	20.8	20.4	19.5
Stress	21.5	20.5	20.1	18.6	18.3	17.7	17.1
LSD P=.05	2.22	2.29	2.28	2.65	2.60	2.86	3.14

Table 12. Volumetric Soil Moisture Content for Irrigation Treatments at the 10-15cm Depth, 1991, continued.

Irrigation Treatments	Date					
	6/21	6/27	6/28	6/29	6/30	7/1
Field Capacity	24.8	24.8	24.9	24.9	24.9	24.9
.25cm Daily	18.9	23.1	22.0	21.1	20.7	20.2
Stress	22.4	21.0	19.9	18.8	24.8	24.0
LSD P=.05	2.79	2.96	2.96	3.51	2.80	2.75

Table 12. Volumetric Soil Moisture Content for Irrigation Treatments at the 10-15cm Depth, 1991, continued.

Irrigation Treatments	Date					
	7/13	7/14	7/15	7/18	7/19	7/20
Field Capacity	26.7	26.7	25.9	25.8	25.9	25.6
.25cm Daily	24.6	24.8	24.1	22.2	21.7	21.0
Stress	21.8	21.8	20.7	22.4	21.2	19.6
LSD P=.05	3.52	3.35	3.55	3.50	4.19	3.72

Table 12. Volumetric Soil Moisture Content for Irrigation Treatments at the 10-15cm Depth, 1991, continued.

Irrigation Treatments	Date				
	7/22	7/25	7/26	7/27	7/28
Field Capacity	30.7	25.7	26.0	26.0	26.1
.25cm Daily	22.2	20.6	20.2	20.0	19.9
Stress	27.6	22.5	21.1	20.0	19.4
LSD P=.05	4.23	3.50	3.11	3.38	3.72

Table 12. Volumetric Soil Moisture Content for Irrigation Treatments at the 10-15cm Depth, 1991, continued.

Irrigation Treatments	Date					
	8/7	8/13	8/14	8/15	8/16	8/17
Field Capacity	25.6	26.3	25.9	26.4	25.9	28.6
.25cm Daily	24.4	26.1	25.5	25.1	24.2	27.0
Stress	21.1	23.6	22.5	21.8	20.7	23.1
LSD P=.05	2.79	2.09	2.02	2.2	2.65	2.56

Table 12. Volumetric Soil Moisture Content for Irrigation Treatments at the 10-15cm Depth, 1991, continued.

Irrigation Treatments	Date					
	8/23	8/24	8/25	8/26	8/29	9/3
Field Capacity	26.3	26.0	25.9	26.2	26.1	26.2
.25cm Daily	26.2	25.6	25.0	24.5	23.4	25.7
Stress	22.4	21.7	20.7	20.0	23.1	23.3
LSD P=.05	2.09	2.15	2.38	2.83	2.31	2.18

Table 12. Volumetric Soil Moisture Content for Irrigation Treatments at the 10-15cm Depth, 1991, continued.

Irrigation Treatment	Date			
	9/6	9/7	9/8	9/9
Field Capacity	26.9	26.3	26.4	26.3
.25cm Daily	26.8	26.3	26.0	25.8
Stress	23.5	22.3	21.9	21.3
LSD P=.05	2.22	2.09	2.16	2.18

Soil Moisture Differences for the 15-25cm Depth Across Treatments

The volumetric soil moisture data for the lowest depth, 15-25cm, are presented in Table 13. There were 37 dates with significant differences. Field capacity treatment had greater moisture than the stress treatment on all but 3 dates. Field capacity was greater than .25cm daily on 16 dates, mostly early in the season as noted in 5-10cm and 10-15cm depths. The 15-25cm depth never reached field capacity. The total moisture measurements were based upon readings averaged over all depths. The 0-5cm depth was often above field capacity and the 15-25cm depth did not reach field capacity. This may explain why the 15-25cm depth did not reach field capacity but did not bring the total profile under 28.1%. Figure 22 follows the moisture content at the 15-25cm depth.

Table 13. Volumetric Soil Moisture Content for Irrigation Treatments at the 15-25cm Depth, 1991.

Irrigation Treatments	Date						
	6/14	6/15	6/16	6/17	6/18	6/19	6/20
Field Capacity	23.0	23.6	24.0	23.8	23.7	23.6	23.3
.25cm Daily	22.7	22.3	21.8	21.3	20.6	20.1	19.5
Stress	20.8	20.1	19.8	18.8	18.1	17.5	17.1
LSD P=.05	2.22	2.29	2.28	2.65	2.60	2.86	3.14

Table 13. Volumetric Soil Moisture Content for Irrigation Treatments at the 15-25cm Depth, 1991, continued.

Irrigation Treatments	Date						
	6/21	6/27	6/28	6/29	6/30	7/13	7/14
Field Capacity	22.7	24.6	24.3	24.4	24.0	25.1	25.3
.25cm Daily	19.4	22.7	21.8	20.8	20.6	23.6	23.7
Stress	19.1	20.8	19.9	18.7	21.8	21.5	21.6
LSD P=.05	2.79	2.96	2.96	3.51	2.80	3.52	3.35

Table 13. Volumetric Soil Moisture Content for Irrigation Treatments at the 15-25cm Depth, 1991, continued.

Irrigation Treatments	Date						
	7/15	7/20	7/22	7/25	7/26	7/27	7/28
Field Capacity	25.1	24.7	27.5	25.1	25.0	25.1	25.0
.25cm Daily	23.1	20.6	20.6	20.2	19.8	19.5	19.5
Stress	20.5	20.0	25.2	22.7	21.2	20.4	19.6
LSD P=.05	3.55	3.72	4.23	3.50	3.11	3.38	3.72

Table 13. Volumetric Soil Moisture Content for Irrigation Treatments at the 15-25cm Depth, 1991, continued.

Irrigation Treatments	Date						
	8/6	8/7	8/9	8/13	8/14	8/15	8/16
Field Capacity	25.6	24.9	29.9	25.7	25.4	25.5	25.1
.25cm Daily	24.4	23.8	26.9	25.0	24.4	24.2	23.6
Stress	22.4	21.3	25.8	23.7	22.7	21.9	20.2
LSD P=.05	2.72	2.79	1.84	2.09	2.02	2.20	2.65

Table 13. Volumetric Soil Moisture Content for Irrigation Treatments at the 15-25cm Depth, 1991, continued.

Irrigation Treatments	Date					
	8/17	8/23	8/24	8/25	8/26	8/29
Field Capacity	27.8	25.7	25.5	25.2	25.2	25.1
.25cm Daily	25.2	25.2	24.8	24.2	23.8	22.7
Stress	22.0	22.6	22.0	20.8	20.1	22.6
LSD P=.05	2.56	2.09	2.15	2.38	2.83	2.31

Table 13. Volumetric Soil Moisture Content for Irrigation Treatments at the 15-25cm Depth, 1991, continued.

Irrigation Treatment	Date		
	9/7	9/8	9/9
Field Capacity	25.4	25.4	25.5
.25cm Daily	25.0	24.8	24.6
Stress	22.7	22.2	21.3
LSD P=.05	2.09	2.16	2.18

PLANT RESPONSES

Irrigation Effects on Turfgrass Quality

Eleven quality ratings were taken on approximately weekly intervals. The data was analyzed as a split plot design. There were two dates where the main irrigation effect was significant, three where species differences were significant, and seven dates with strong interactions. Table 14 lists the quality rating data for irrigation treatments over both species for the 2 dates where differences occurred. On both dates the field capacity and .25cm daily treatments had higher quality than the stress treatment.

For the three dates with significant differences between species over the irrigation treatments (Table 15) the creeping bentgrass had higher quality than the annual bluegrass.

When comparing turfgrass quality between species within the field capacity treatment (Table 16) creeping bentgrass had higher quality on 4 of the 7 dates. No differences were found on the other dates. For the .25cm daily treatment (Table 17) creeping bentgrass had higher quality on 6 of the 7 dates. The stress treatment (Table 18) showed creeping bentgrass of consistently higher quality on all dates.

Table 14. Turfgrass Quality Ratings, for Irrigation Treatments Across Species. 9=excellent 1=dead turf

Treatment	Date	
	6/19	9/5
Field Capacity	6.3	8.0
.25cm Daily	6.0	7.9
Stress	4.8	7.2
LSD P=.05	.60	.50

Table 15. Turfgrass Quality Ratings, for Species Across Irrigation Treatments. 9=excellent 1=dead turf

Species	Date		
	6/19	7/8	9/11
Bentgrass	6.7	7.3	8.1
Annual Bluegrass	4.8	5.9	7.7
LSD P=.05	.38	.62	.33

Table 16. Turfgrass Quality Ratings for Species, Field Capacity Treatment, 1991.

Species	Date			
	7/15	7/28	8/14	8/26
Bentgrass	8.0	8.2	7.5	8.5
Annual Bluegrass	6.7	7.2	7.0	8.0
LSD P=.05	1.30	0.78	0.41	0.33

Table 17. Turfgrass Quality Ratings for Species, .25cm Daily Treatment, 1991.

Species	Date					
	6/26	7/15	7/21	7/28	8/14	8/26
Bentgrass	6.7	8.0	8.0	8.0	7.7	8.2
Annual Bluegrass	5.3	6.0	5.7	6.7	7.2	7.3
LSD P=.05	0.66	1.30	1.05	0.78	0.41	0.33

Table 18. Turfgrass Quality Ratings for Species, Stress Treatment, 1991.

Species	Date						
	6/29	7/15	7/21	7/28	8/7	8/14	8/26
Bentgrass	6.0	7.3	7.0	7.0	7.0	7.2	7.3
Annual Bluegrass	4.0	3.7	3.7	4.3	5.0	5.2	5.2
LSD P=.05	0.66	1.30	1.05	0.78	0.66	0.41	0.33

The data for comparisons of turf quality among irrigation treatments within a species are given in Tables 19 and 20 for bentgrass and annual bluegrass, respectively. For bentgrass, the field capacity treatment had higher quality than the stress treatment on 4 of 7 dates when significant differences occurred. While the .25cm daily treatment was better than the stress treatment on 3 of 7 dates. There were no differences between the field capacity and .25cm daily treatments.

For annual bluegrass the separation in quality ratings is more clear (Table 20). On 2 dates the quality ratings for the field capacity plots were better than the .25cm daily treatment. The stress treatment plots ranked lower than both field capacity and .25cm daily treatments. These results show clearly that annual bluegrass did not tolerate moisture stress as well as creeping bentgrass.

Table 19. Bentgrass Turfgrass Quality Ratings for Irrigation Treatments, 1991. 9=excellent 1=dead turf				
Irrigation Treatment	Date			
	6/29	7/21	7/28	8/26
Field Capacity	7.3	8.0	8.2	8.5
.25cm Daily	6.7	8.0	8.0	8.2
Stress	6.0	7.0	7.0	7.3
LSD P=.05	1.0	1.0	.78	.72

Table 20. Annual Bluegrass Turfgrass Quality Ratings for Irrigation Treatments, 1991. 9=excellent 1=dead							
Irrigation Treatment	Date						
	6/29	7/15	7/21	7/28	8/7	8/14	8/26
Field Capacity	7.0	6.7	7.0	7.2	7.3	7.0	8.0
.25cm Daily	5.3	6.2	5.7	6.7	6.7	7.2	7.3
Stress	4.0	4.8	3.7	4.3	5.0	5.2	5.2
LSD P=.05	1.0	1.0	1.0	.78	.74	.44	.72

Irrigation Effects on Clipping Weight

Eleven dates were selected at approximately one week intervals for collecting clippings. Only four dates had significant differences. Irrigation treatment differences were found on 2 dates (Table 21) with the field capacity and .25cm daily treatments producing more clippings than the stress treatment. Differences between species were also found for 2 dates (Table 22) with the creeping bentgrass producing more clippings than the annual bluegrass.

There was one date of irrigation by species interaction. On that date irrigation treatments within a species were not significant. For the same date there were differences (Table 23) between species for the same irrigation treatment.

Table 21. Clipping Weights for Irrigation Treatments Across Species, 1991. Grams per square meter.

Irrigation Treatment	Date	
	7/15	8/29
Field Capacity	41.4	39.9
.25cm Daily	34.9	40.2
Stress	26.5	24.0
LSD P=.05	8.5	9.3

Table 22. Clipping Weights for Species Across Irrigation Treatments, 1991. Grams per square meter.

Irrigation Treatment	Date	
	7/15	8/29
Creeping Bentgrass	38.5	36.7
Annual Bluegrass	30.0	32.7
LSD P=.05	5.7	NS

Table 23. July 7, 1991 Clipping Weights for Species within an Irrigation Treatment. Grams per square meter.

	Irrigation Treatments		
Species	Field Capacity	.25cm Daily	Stress
Creeping Bentgrass	31.8	32.1	29.4
Annual Bluegrass	24.1	23.3	19.6
LSD P=.05	6.3	6.3	6.3

<u>Irrigation Effects on Turfgrass Rooting</u>

Root samples were taken from all four depths on July 17 and September 4, 1991. There was no effect of irrigation differences on rooting. On July 17 significant differences were found between species and among depths (Tables 24 and 25). Bentgrass produced more roots than annual bluegrass. The surface level had more roots than the lower three depths while the lower three depths were not different from each other on July 17.

There was a species by depth interaction on September 4, 1991. The first comparison is individual species at each depth. Creeping bentgrass (Table 26) had greater root weights in the 0-5cm depth than all other levels, while the 5-10cm depth had more roots than the 15-25cm depth. Annual bluegrass (Table 27) showed no difference between the 0-5cm and 5-10cm depths. The 0-5cm depth had greater root weights than the 10-15cm and 15-25cm depths.

When comparing the species at a single depth (Tables 28, 29, 30, 31), creeping bentgrass produced more roots than annual bluegrass in the 0-5cm and 5-10cm depths.

Table 24. July 17, 1991 Irrigation Effects on Species Root Weights in the 0-25cm depth. Kg/M^3

Species	
Creeping Bentgrass	1.70
Annual Bluegrass	0.91
LSD P=.05	0.43

Table 25. July 17, 1991 Irrigation Effects on Rooting Depth, 1991. Kg/M³

Depth	
0-5cm	3.42
5-10cm	0.82
10-15cm	0.59
15-25cm	0.38
LSD P=.05	0.70

Table 26. September 4, 1991 Bentgrass by Depth Effects on Rooting Across Irrigation Treatments. Kg/M³

Depth	
0-5cm	5.1
5-10cm	2.0
10-15cm	1.0
15-25cm	0.6
LSD P=.05	1.1

Table 27. September 4, 1991 Annual Bluegrass by Depth Effects on Rooting Across Irrigation Treatments. Kg/M³

Depth	
0-5cm	1.9
5-10cm	1.0
10-15cm	0.6
15-25cm	0.3
LSD P=.05	1.1

Table 28. September 4, 1991 Rooting differences between Species at the 0-5cm depth.	
Species	
Creeping Bentgrass	5.1
Annual Bluegrass	1.9
LSD P=.05	1.0

Table 29. September 4, 1991 Rooting differences between Species at the 5-10cm depth.	
Species	
Creeping Bentgrass	2.0
Annual Bluegrass	0.9
LSD P=.05	1.0

Table 30. September 4, 1991 Rooting differences between Species at the 10-15cm depth.	
Species	
Creeping Bentgrass	1.0
Annual Bluegrass	0.6
LSD P=.05	NS

Table 31. September 4, 1991 Rooting differences between Species at the 10-15cm depth.	
Species	
Creeping Bentgrass	0.6
Annual Bluegrass	0.3
LSD P=.05	NS

DISCUSSION

TDR Volumetric Soil Moisture Data

The TDR system worked as well as the system used by Topp (1987), proving that the system is accurate in a sandy loam soil under turf conditions. TDR volumetric soil moisture measurements were strongly correlated with the gravimetric sampling. The placement of the wave guides was also successful and provided information for irrigation scheduling and the amount of soil water present in the four depths investigated. We found that the horizontal placement of the wave guides needed to be 2.5cm below the soil surface, not the 2cm therorized by Baker and Lascano (1989). When the wave guides were placed closer than 2.5cm to the surface the measurements erred toward very dry readings. It may be that the area of wave influence was extending into the thatch and/or air, resulting in the dry readings. The distance from the surface was altered from the Baker and Lascano testing (1989), but the elipse of influence of the wave guide pairs as described in the same work was very close. This is supported by the high degree of correlation at each depth.

The final hardware and software configurations in the

TDR system proved to be reliable and accurate. Very little maintenance was required on the switches and wave guides. The software program was developed in 1990 and remains unaltered. The extensive irrigation testing was necessary for accurate and uniform application. Without such testing an irrigation study is subject to criticism. Although uniformity rates may be higher in manufacturer specification information than in our testing, it should be noted that manufacturers are listing indoor, controlled results. These are field test uniformity results.

The ability of the system to accurately determine and apply the needed water to return the field capacity plots to field capacity opens many possible uses for this tool. For the researcher, the ability to evaluate turf species at predetermined soil moisture levels will aid in the development of irrigation regimes for different species under varying uses.

Tracking the drying in the .25cm daily treatment illustrated the TDR techniques ability to watch soil moisture changes and relate them to turf responses.

The stress treatment irrigation treatment TDR calculated irrigation events did not bring the soil back to field capacity. Possible reasons for this may be that a large amount of water was required to rewet the thatch. The amount of water lost from the thatch was not measured by the TDR system. In the .25cm daily and field capacity treatments the plots were irrigated or received rainfall almost daily. This very likely kept the thatch moist.

The field capacity irrigation treatment resulted in quite moist plots. If these plots had been subject to traffic, compaction and compaction related problems may have occurred. In practice, the field capacity plots would not have provided acceptable fairway turf, even though they were of high quality, because the excess moisture would not have been an acceptable playing surface.

The .25cm daily plots soil moisture was variable. In the spring and fall, times of low evapotranspiration, the soil moisture in the plots was comparable to the field capacity treatment. During extended dry periods the soil moisture declined until the soil profile was recharged by rainfall.

The stress treatment was very dry for most of the year. This treatment returned to field capacity only after rainfall. One benefit of this treatment was the correlation of TDR and gravimetric soil moisture data at low moistures. The field capacity treatment provided the very moist data, the .25cm daily treatment the mid range soil and dry moisture data, and the stress treatment the very dry information.

The plots did not exceed field capacity in any treatment for the profile, except after a rainfall event. This shows that all three irrigation schedules were not the cause of excess irrigation.

When examining the soil moisture changes by depth for each treatment the trend for the field capacity and .25cm daily treatments was decreasing soil moisture with increasing depth. The 0-5cm depth was the driest for most of the season in the stress treatment. The lowest depth, 15-25cm did not exceed field capacity in any treatment except after heavy rainfall. This indicates that the leaching potential for all three treatments is low. The monitoring of depths generally considered out of the main turfgrass root zone, may be of value to those concerned with leaching of fertilizers or pesticides.

Plant Responses

Only 2 of the 11 quality rating dates showed significant differences in quality among irrigation treatments however, there were strong trends showing the field capacity plots to be of higher quality than .25cm daily and .25cm daily greater than the stress treatment. The low power of main effects in a split plot design may be the reason for the lack of significant differences.

For bentgrass the field capacity and .25cm daily treatments provided equal quality. Annual bluegrass did not provide as high a quality turf under the .25cm daily treatment. Bentgrass tolerated the stress treatment much better than the annual bluegrass.

Bentgrass produced more clippings than annual bluegrass in all treatments.

The rooting data showed the majority of the roots in the 0-5cm and 5-10cm zones. Bentgrass out produced annual bluegrass in total root weights and in the 0-5cm and 5-10cm depths. Those interested in scheduling irrigation may wish to consider monitoring the top 10cm as this is the area of greatest root mass, and thus assumed highest root activity.

The TDR system shows great promise as a research and field tool for monitoring volumetric soil moisture and scheduling irrigation. This method holds the potential of conserving our water resourses, reducing the nutrient and pesticide leaching potential of turfgrass systems and providing high quality turf.

APPENDIX

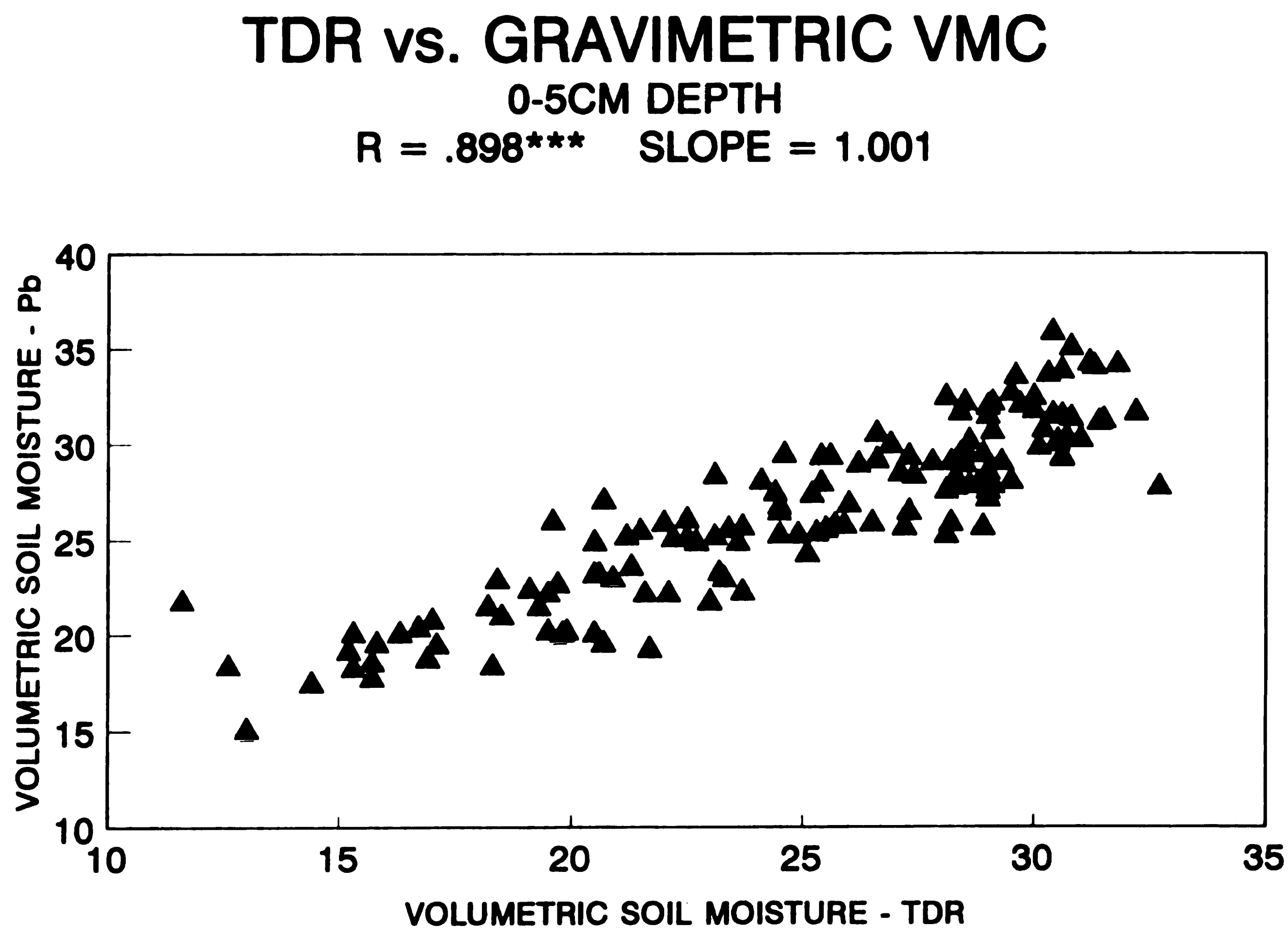

Figure 5. TDR vs. Gravmetric Volumetric Soil Moisture

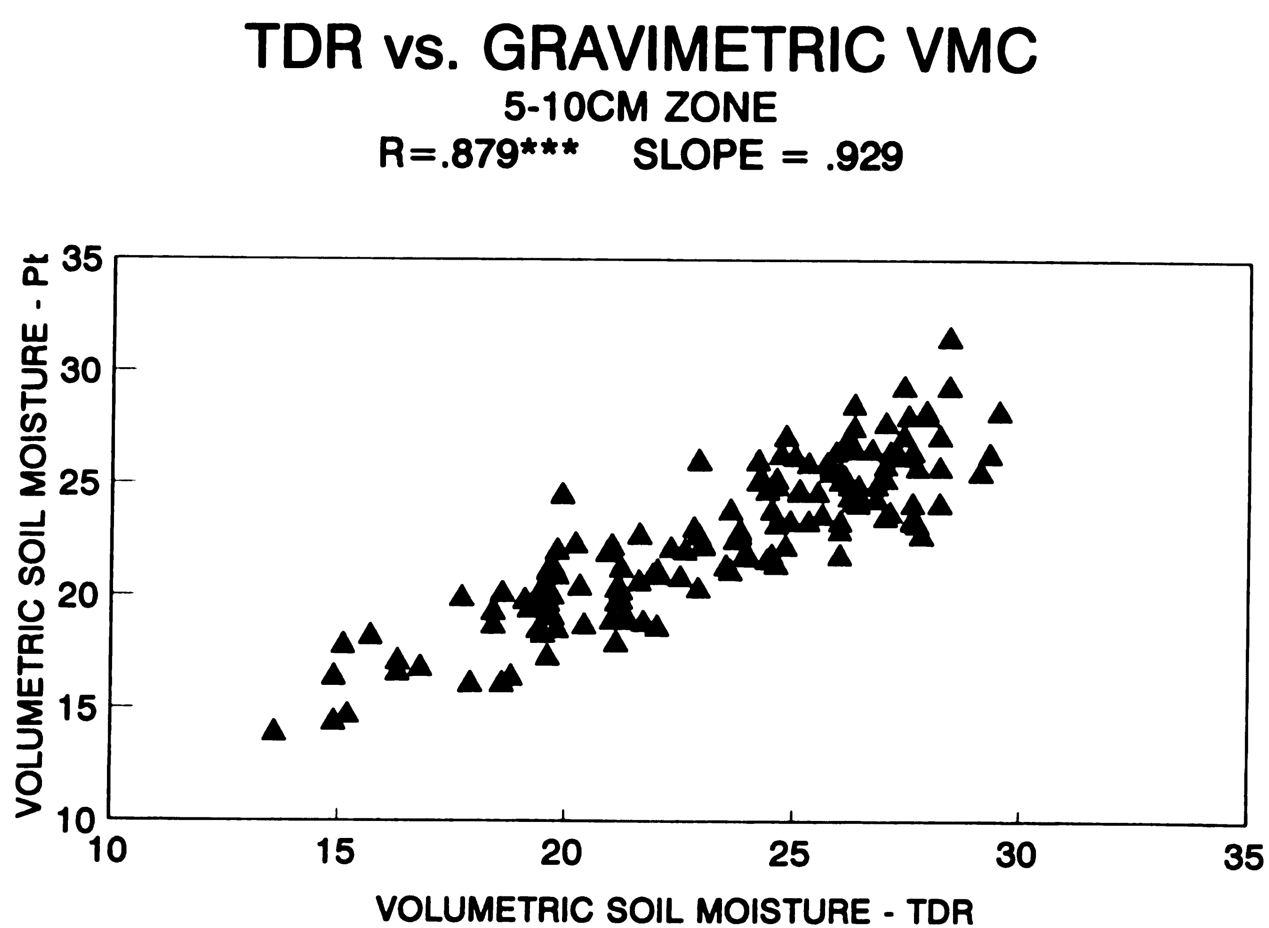

Figure 6. TDR vs. Gravimetric Volumetric Soil Moisture

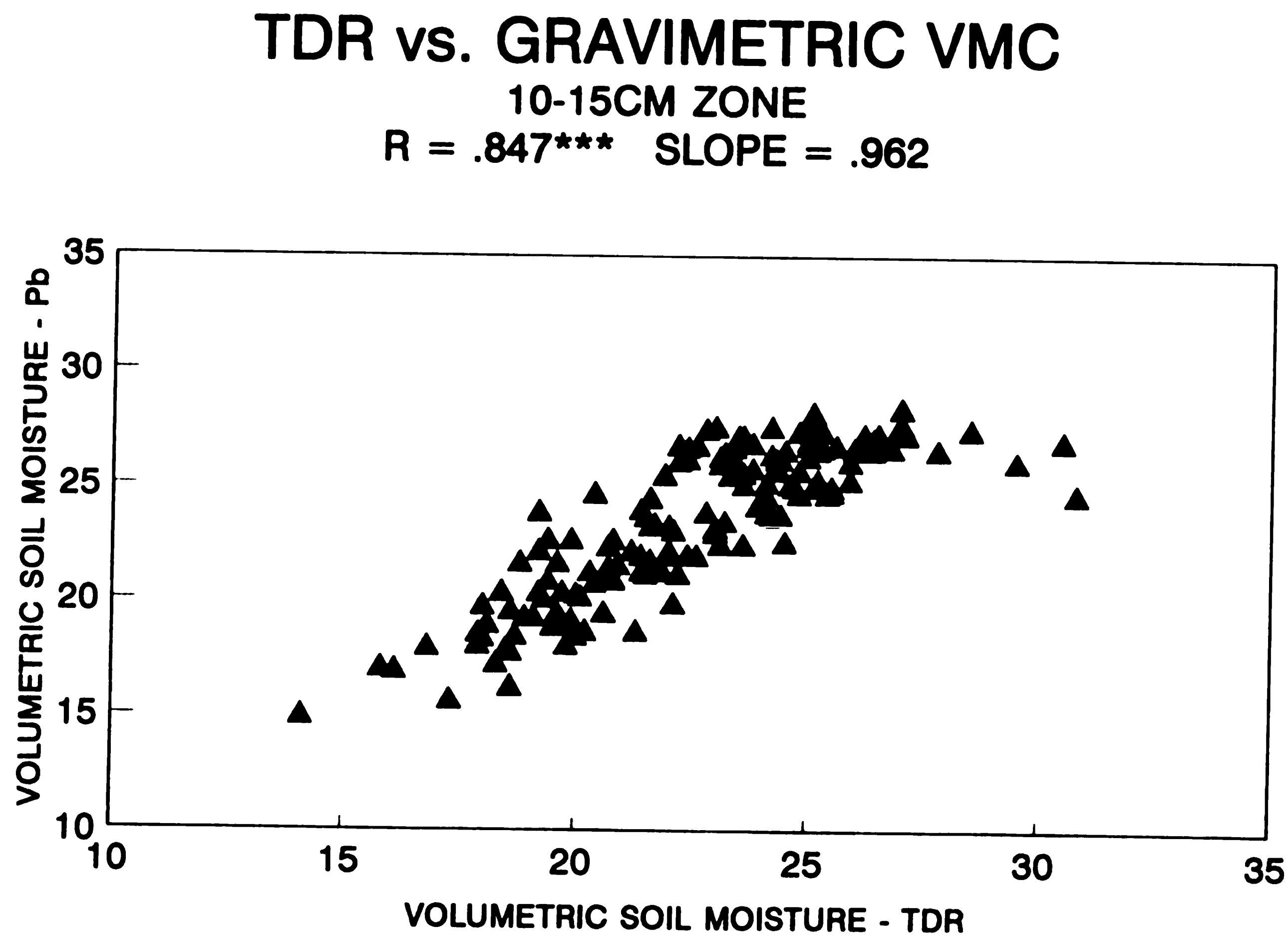

Figure 7. TDR vs. Gravimetric Volumetric Soil Moisture

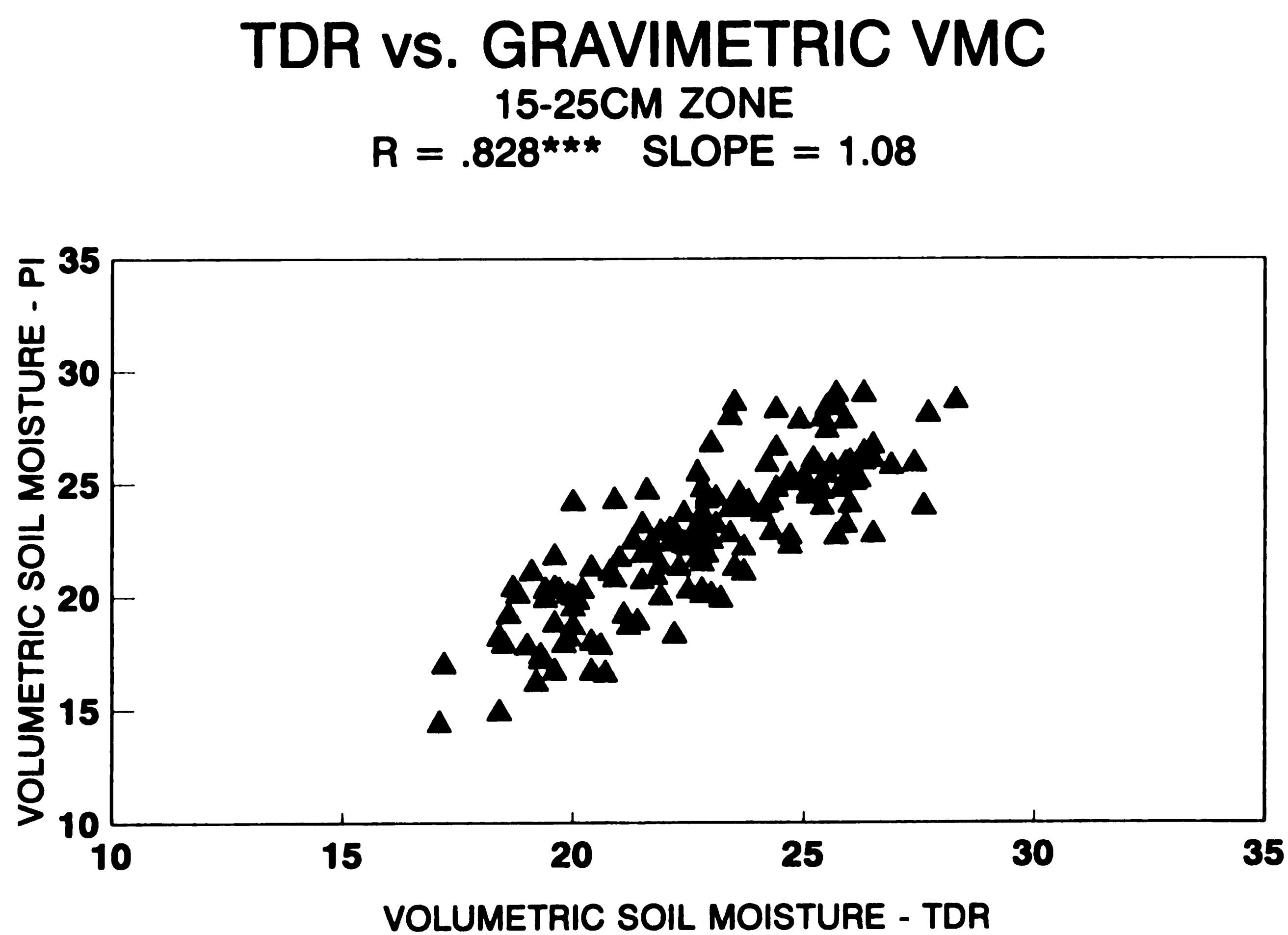

Figure 8. TDR vs. Gravimetric Volumetric Soil Moisture

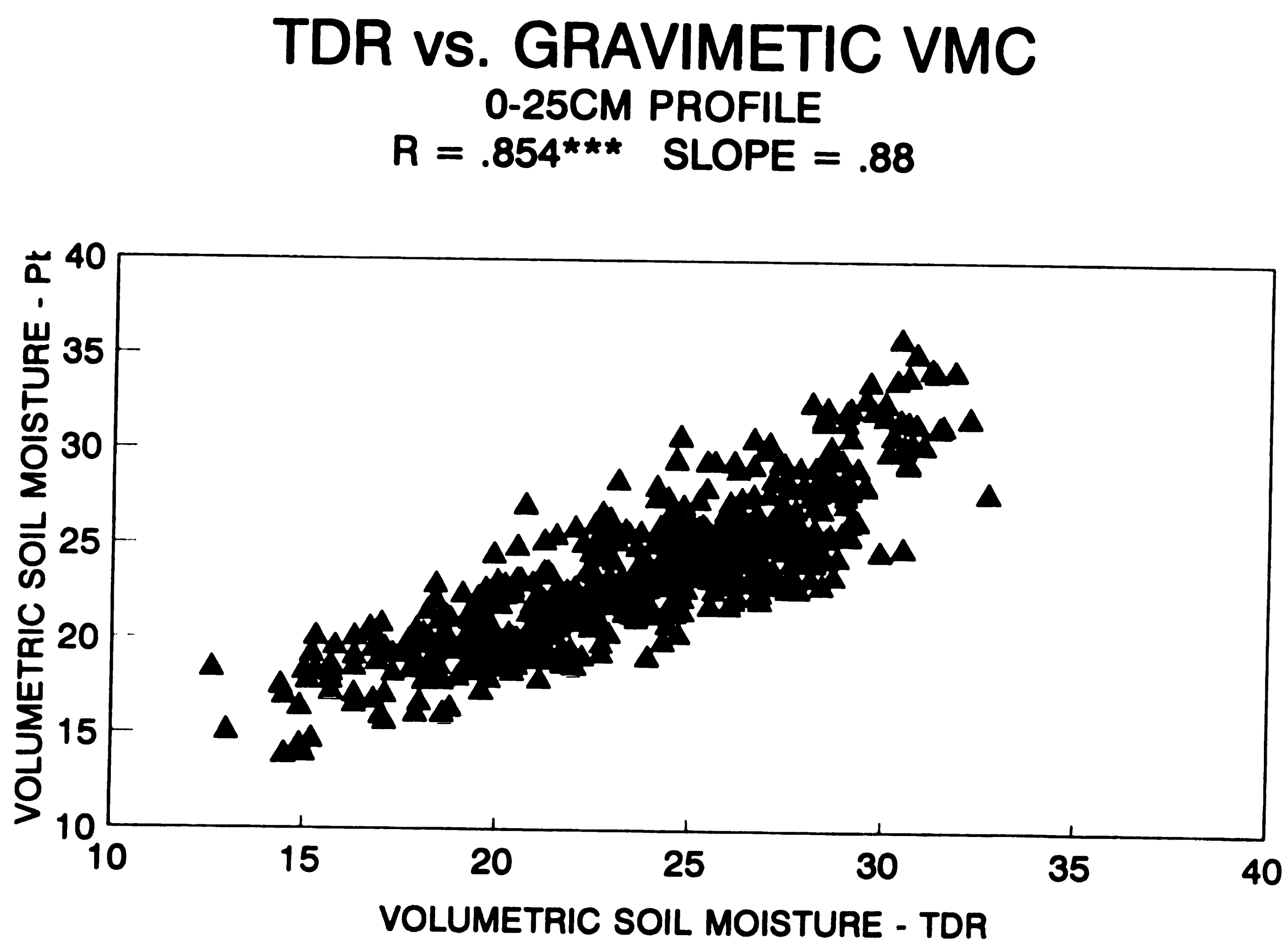

Figure 9. TDR vs. Gravimetric Volumetric Soil Moisture

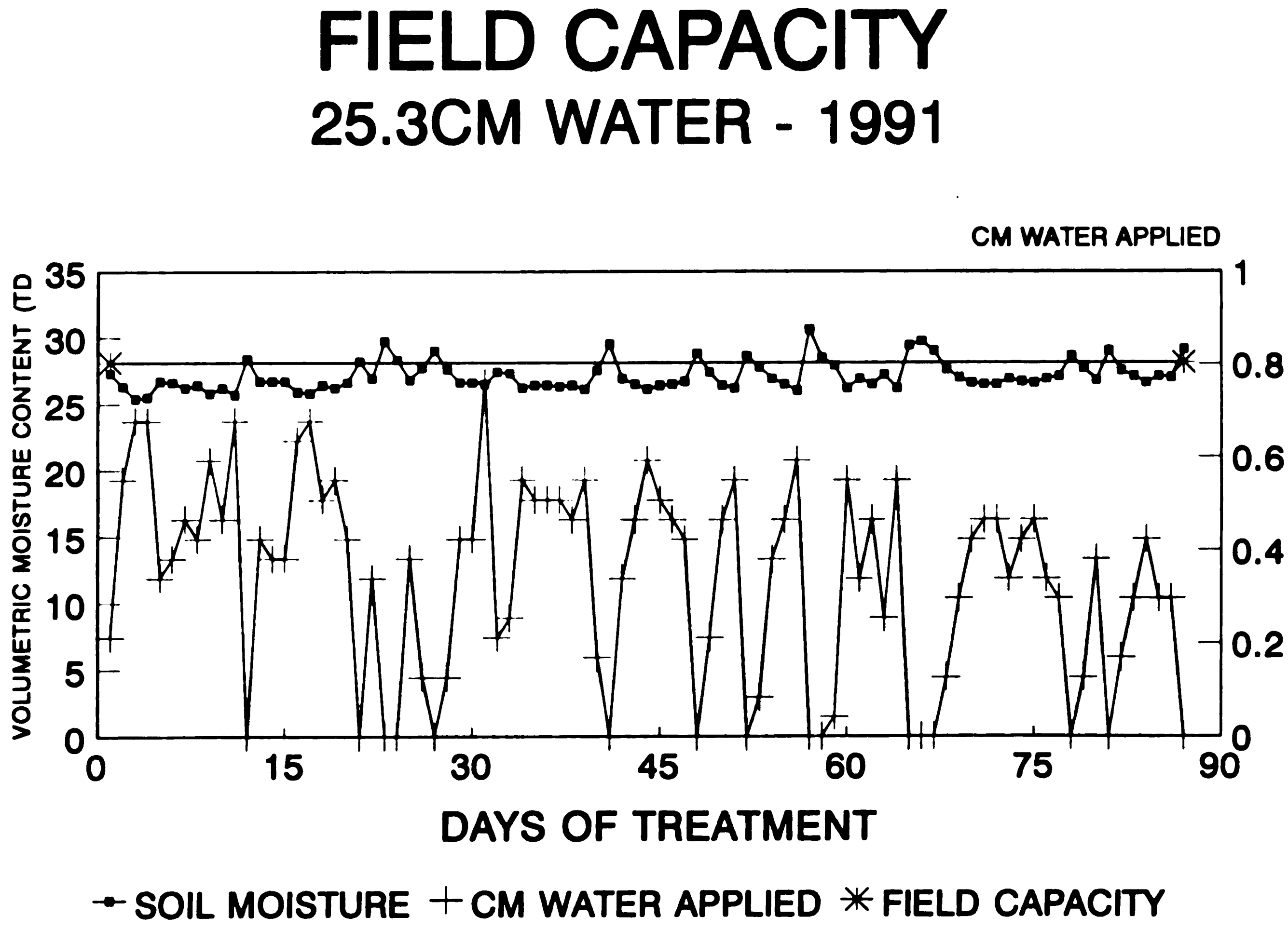

Figure 10. Field Capacity Treatment Soil Moisture and Irrigation Application

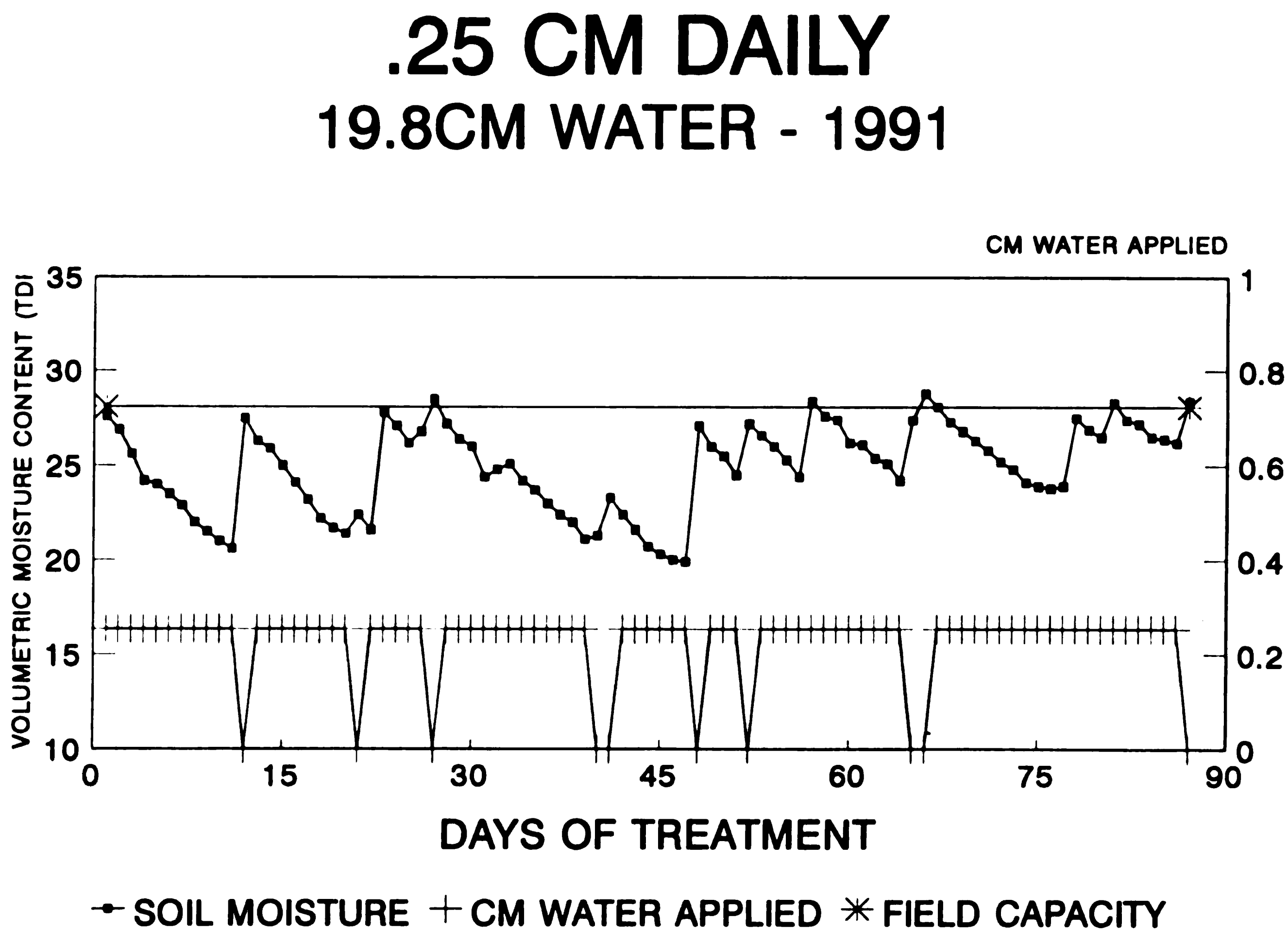

Figure 11. .25cm Daily Treatment Soil Moisture and Irrigation Application

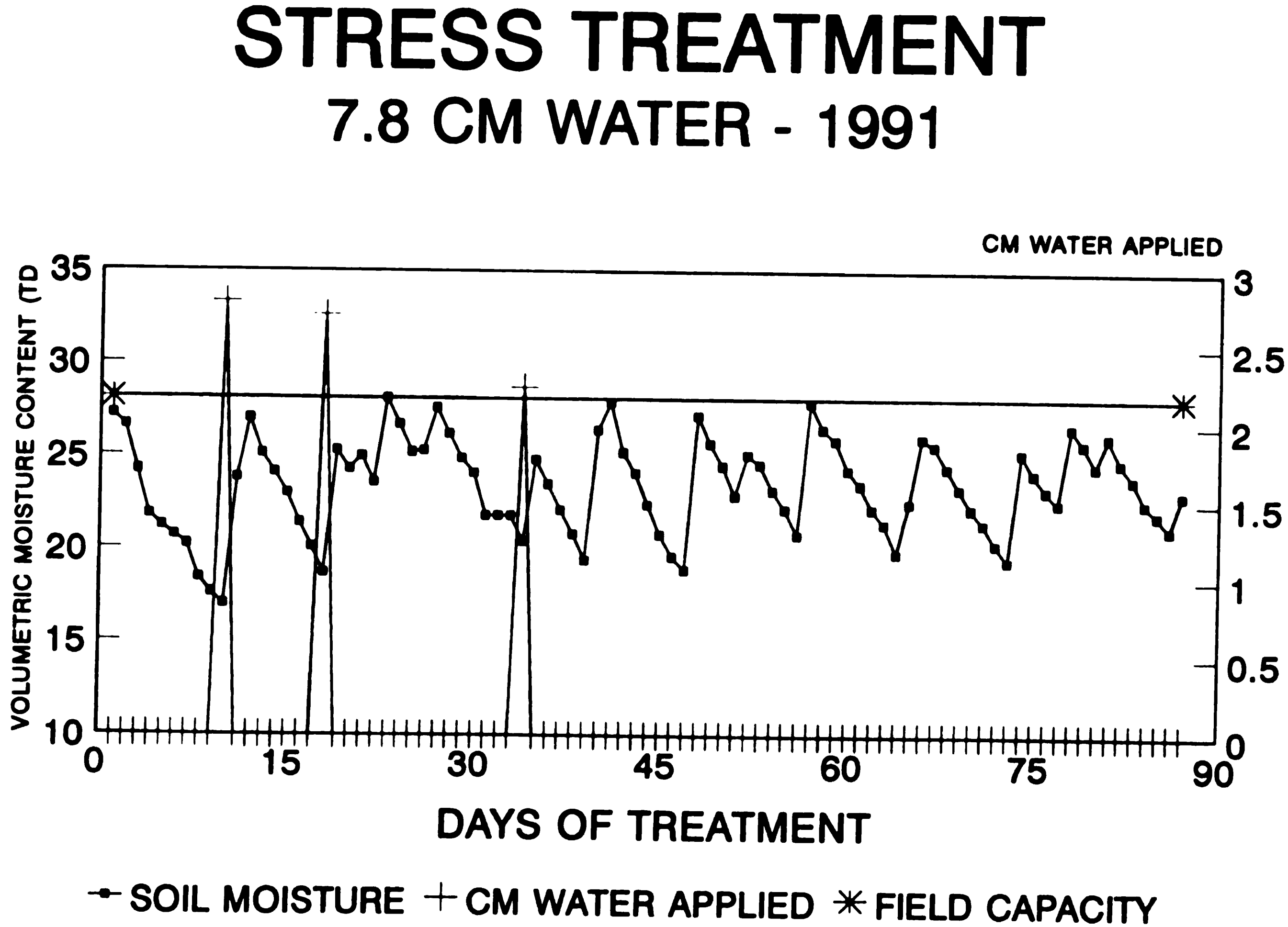

Figure 12. Stress Treatment Soil Moisture and Irrigation Application

IRRIGATION TREATMENT SOIL MOISTURE

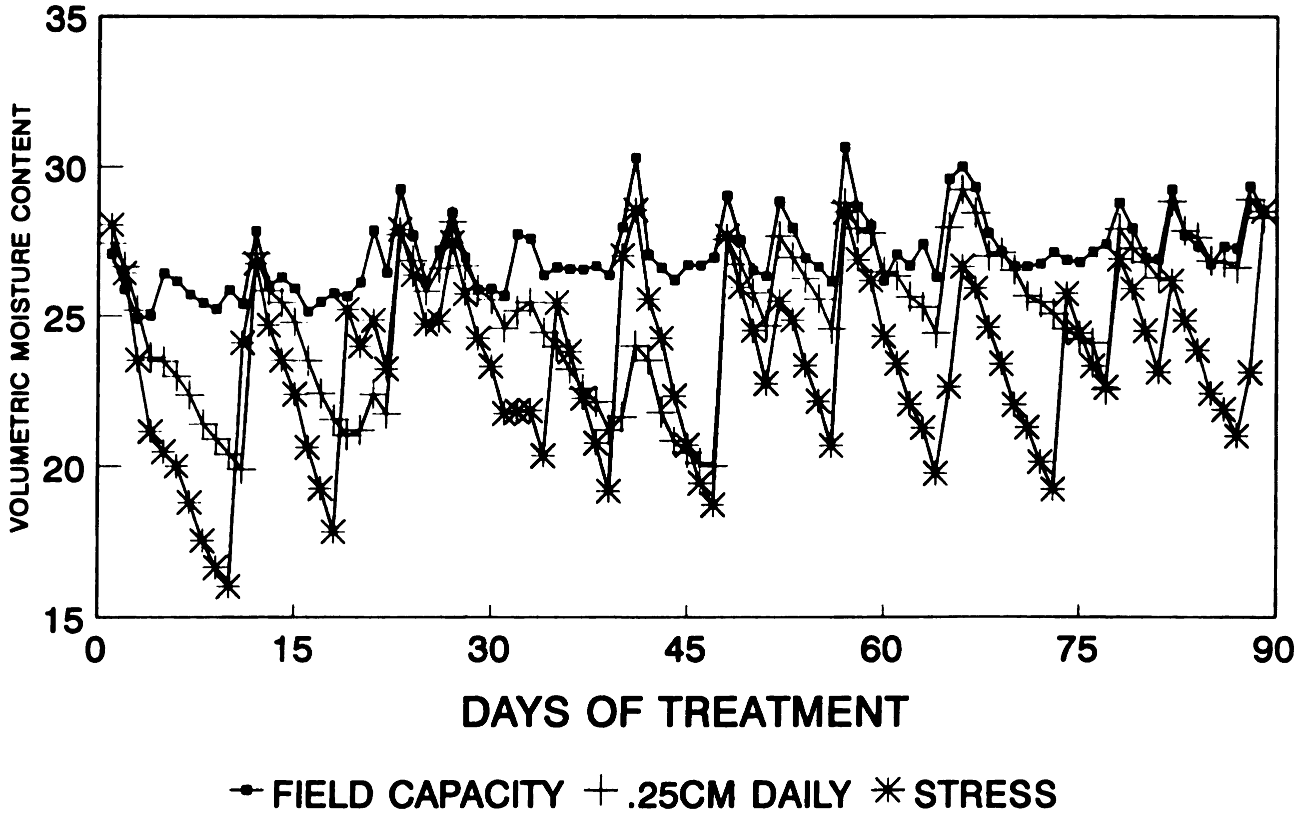

Figure 13. Irrigation Effects on Soil Profile Moisture

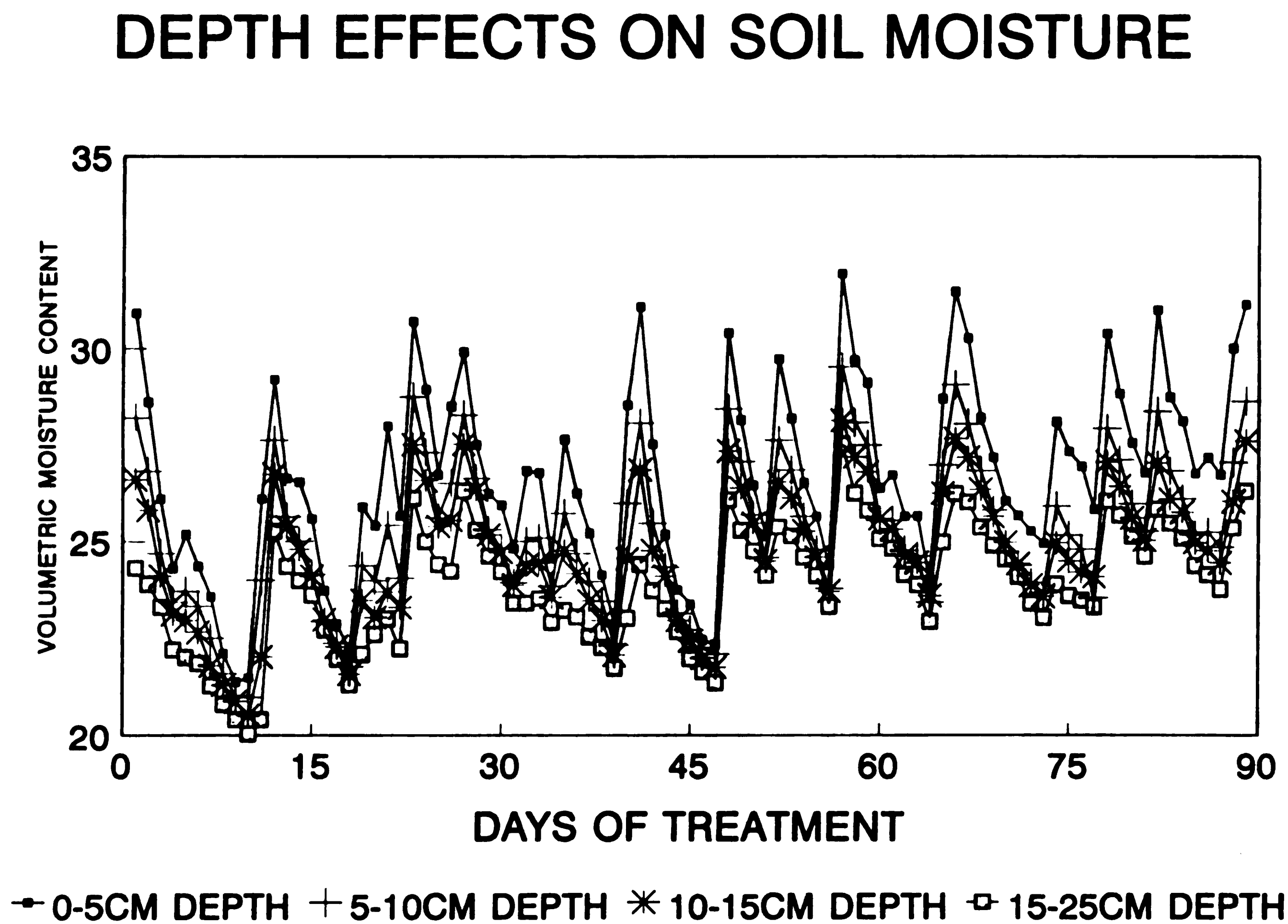

Figure 14. Depth Effects on Soil Moisture

FIELD CAPACITY TREATMENT

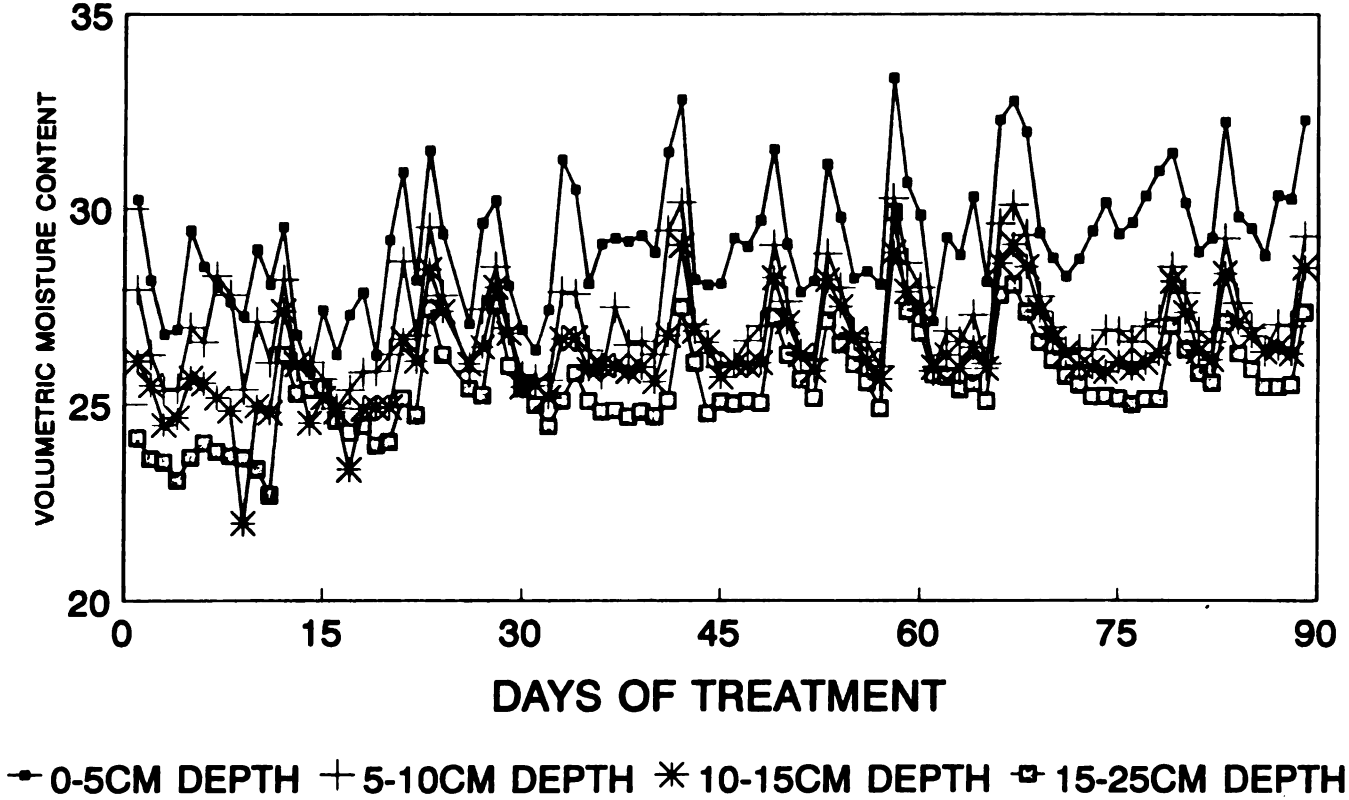

Figure 15. Soil Moisture at Depth, Field Capacity Treatment

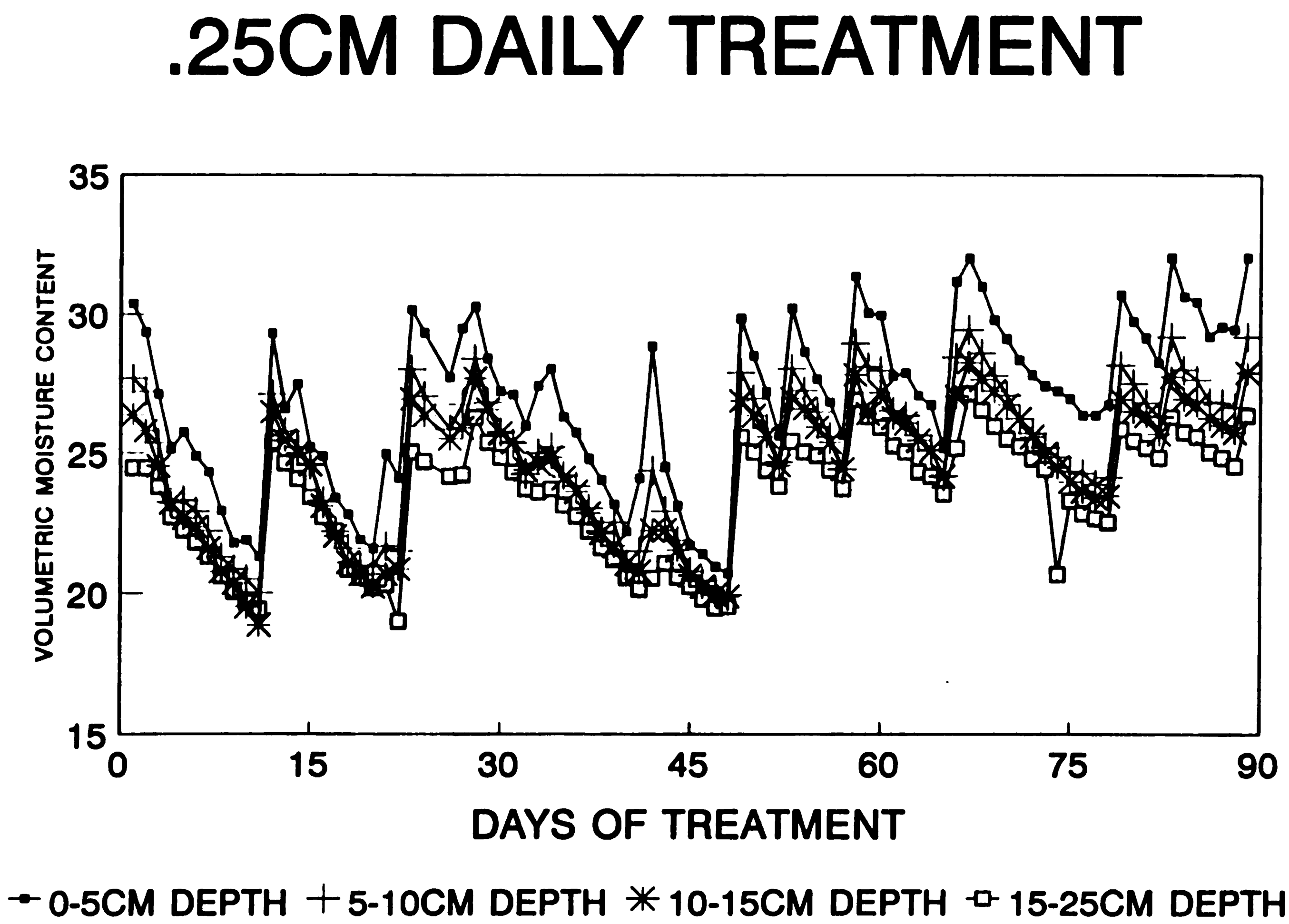

Figure 16. Soil Moisture at Depths, .25cm Daily Treatment

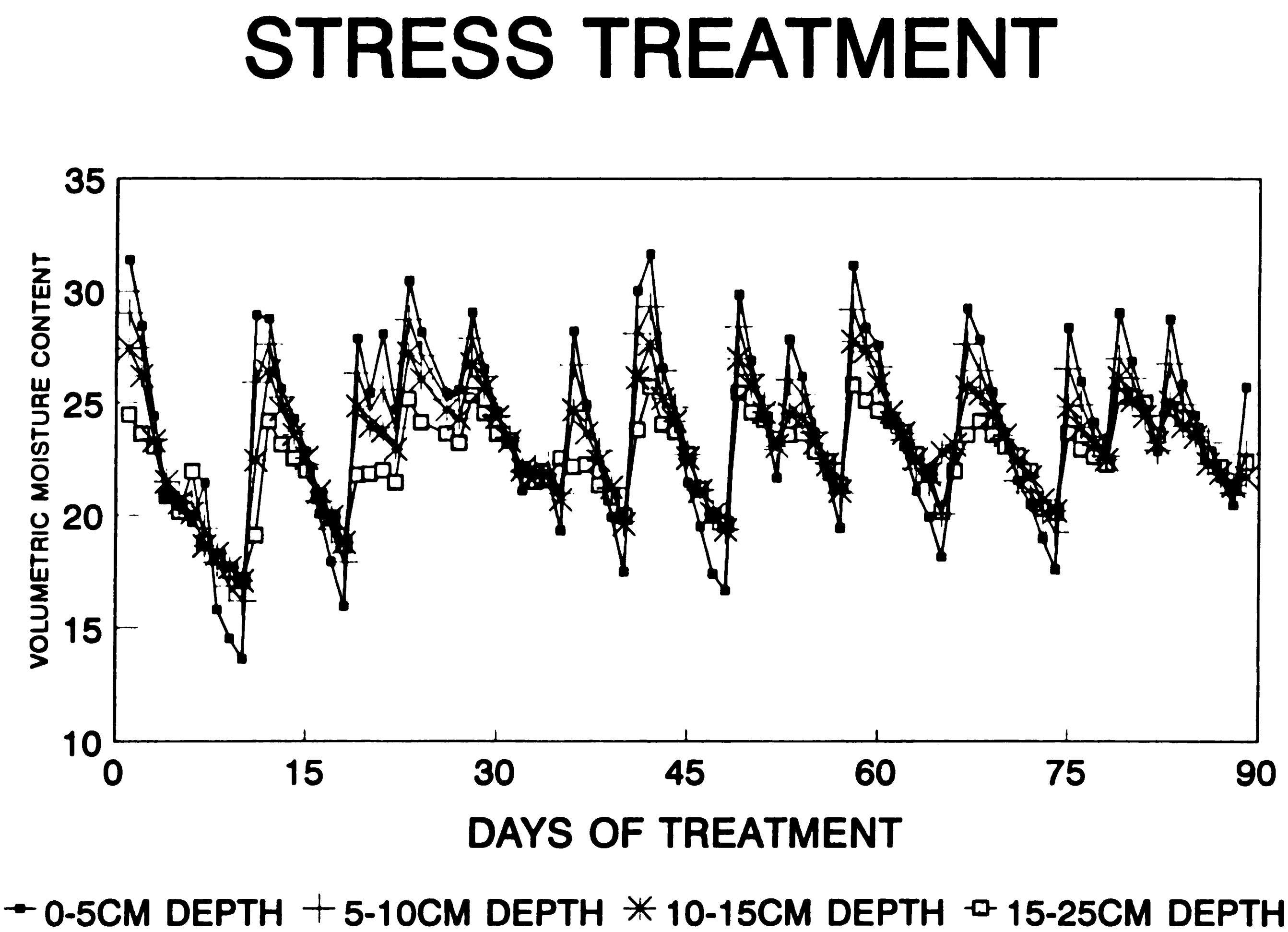

Figure 17. Soil Moisture at Depths, Stress Treatment

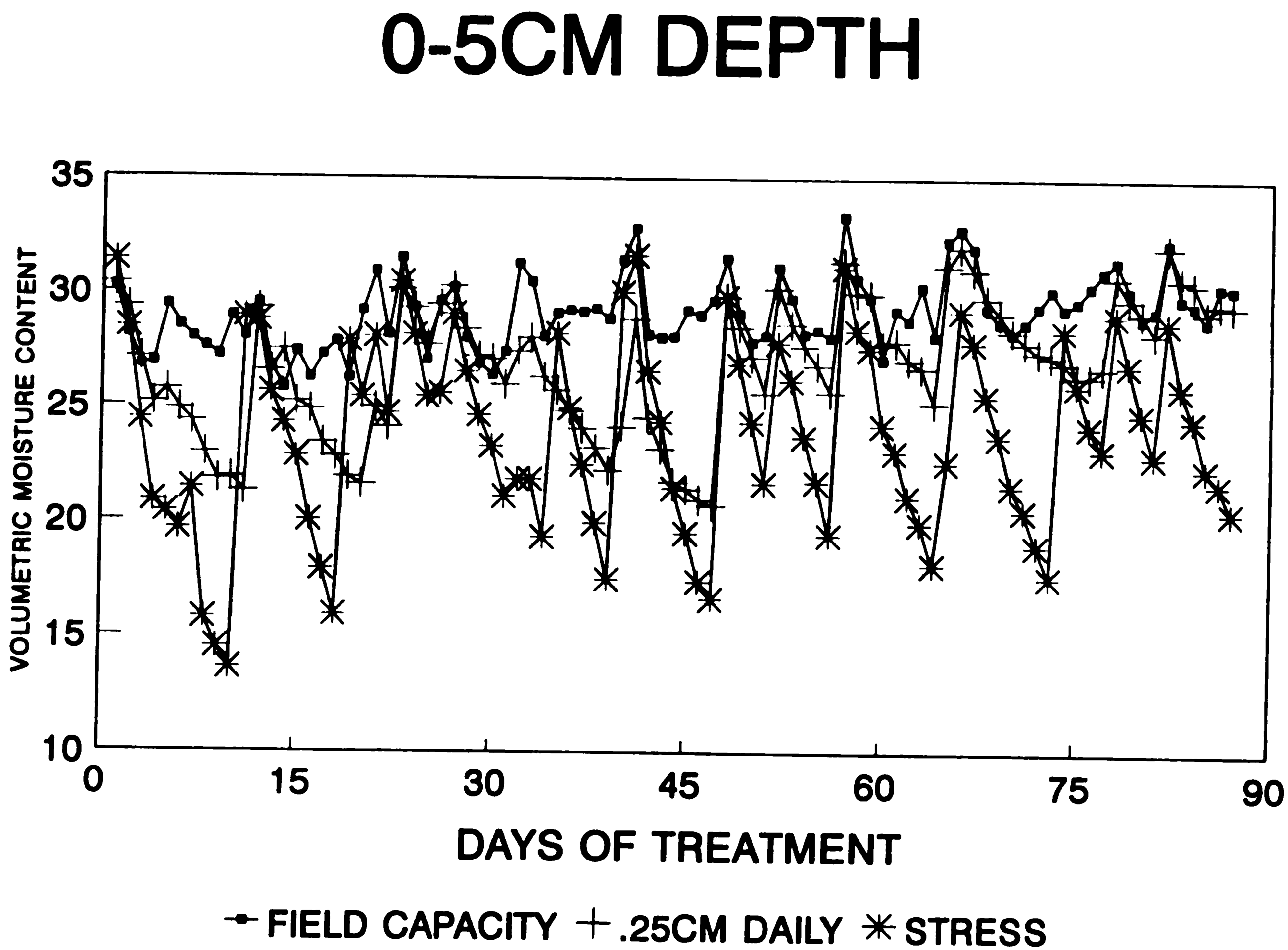

Figure 18. Irrigation Treatment Soil Moisture at 0-5cm Depth

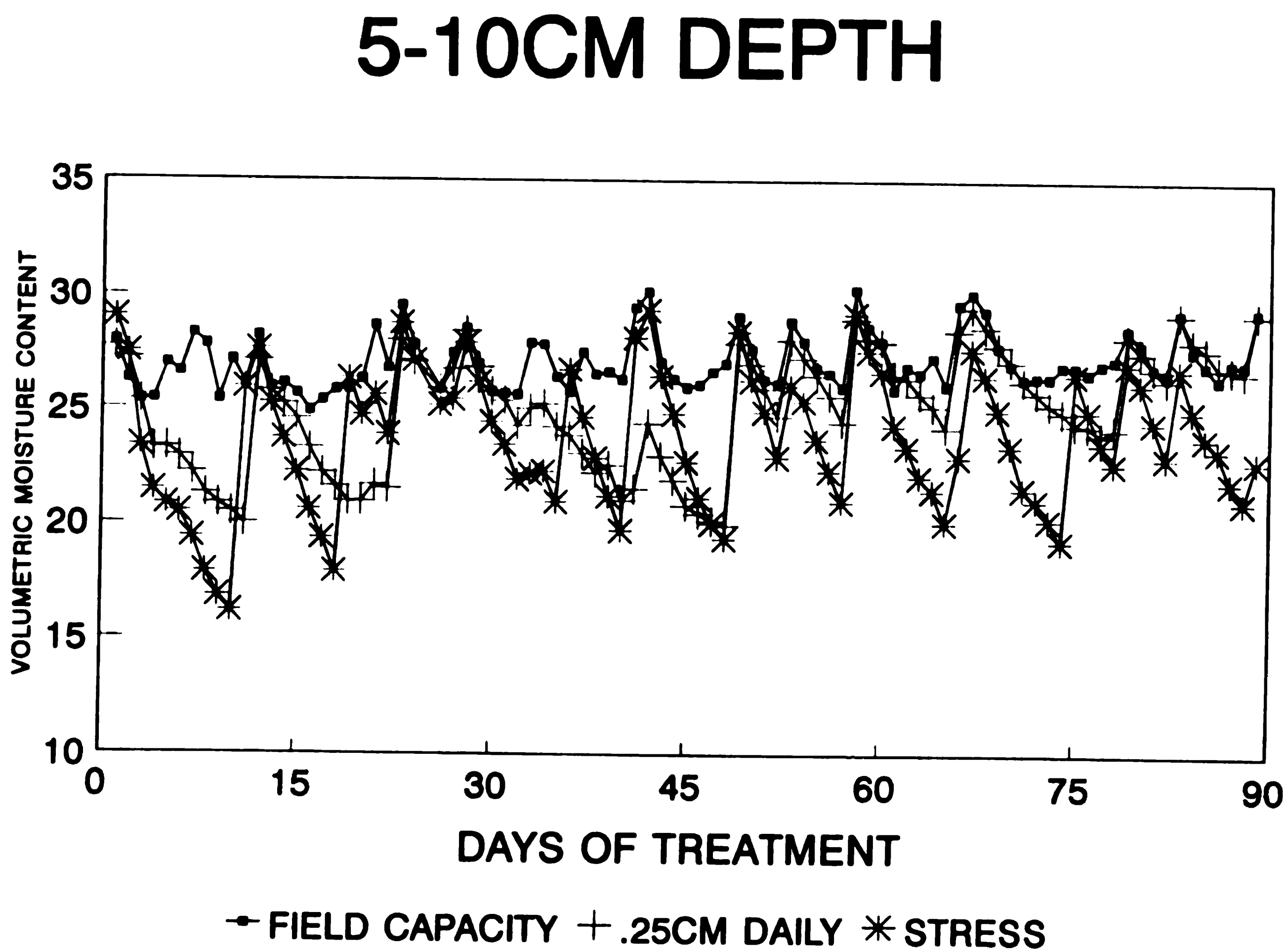

Figure 19. Irrigation Treatment Soil Moisture at 5-10cm Depth

10-15CM DEPTH

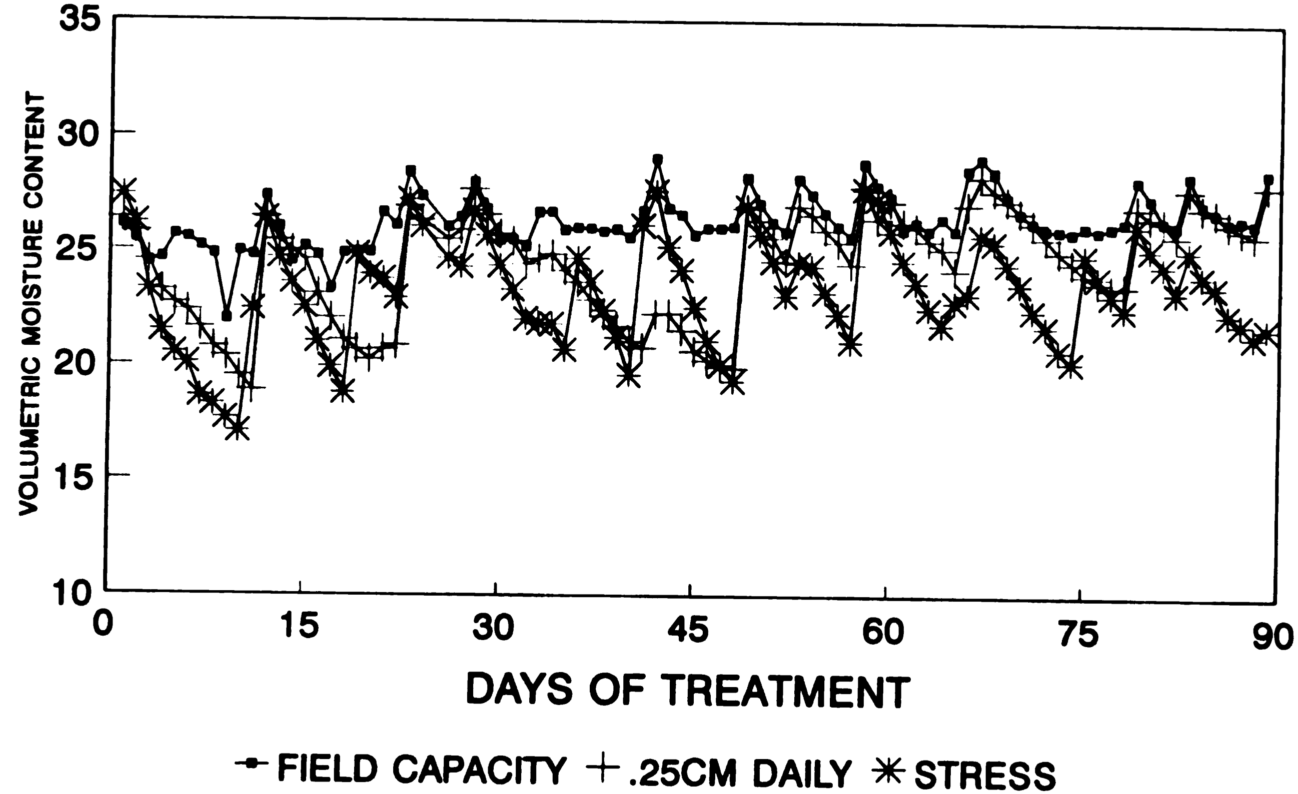

Figure 20. Irrigation Treatment Soil Moisture at 10-15cm Depth

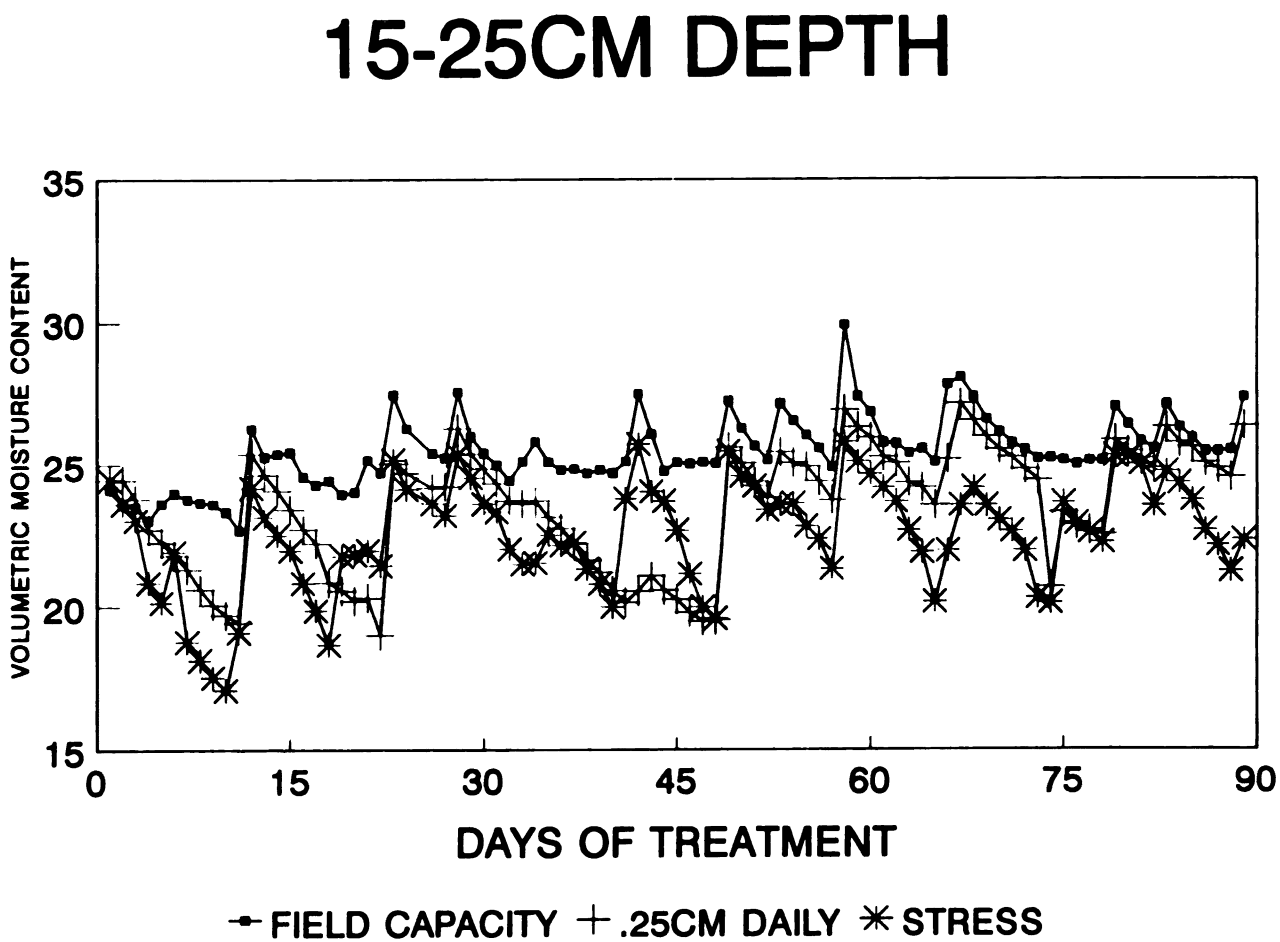

Figure 21. Irrigation Treatment Soil Moisture at 15-25cm Depth

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