LOSS AND UNIFORMITY OF LOW TRAJECTORY CENTER-PIVOT SPRINKLERS

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CENTER-PIVOT SPRINKLERS

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CHAPTER I

INTRODUCTION

The Problem

The Center-Pivot Sprinkler Irrigation System was invented by Frank Zybach of Columbus, Nebraska, about 30 years ago (Splinter, 1976). He developed this machine while farming in Colorado near the town of Strasburg, east of Denver. After many trials and adjustments the system was made to work, and a U.S. patent was granted in 1952.

The system consists of a line of sprinklers of the impact type usually mounted on a 0.15 meter (m) (6 in.) pipe. The most common length is approximately 402 m (1320 ft) and it rotates continuously or periodically about a pivot point at one end. The pipeline is supported by towers spaced approximately 30.5 m (100 ft) apart, each having a drive mechanism and wheels or tracks. Water is pumped into the pipeline from a source, usually underground, at the center of the field and the towers carry the system around the center pivot. The rate at which the towers and the pipeline advance is set by the speed of the outermost tower; an alignment device detects any laggards and moves each tower to align with the one behind it. Thus an advance by the outermost tower sets off a chain reaction of advances beginning with the second tower from the end and progressing backward toward the center of the circle.

The advantages and abilities of a center-pivot system has been summarized by Splinter (1976). It enables the farmer to irrigate large tracts of land automatically. Once the system is set to work, it advances continuously in a circle applying irrigation water without need for further attention other than monitoring and repairing occasional breakdowns. Its ability to apply light and frequent applications is a revolutionary feature. Many agricultural areas are limited in productivity because the soils are sandy or coarse-textured. Such soils hold little water, less than an inch per foot of the soil depth compared with two or more inches per foot for fine-textured or loamy soils. As a result coarse or sandy soils are characteristically dry and can usually serve only for marginal farming. The light, frequent application of water from a center-pivot replenishes the moisture in the root zone sufficiently to allow intensive cropping on these soils. Flat to rolling wheatlands of western Nebraska have easily been converted to irrigated agriculture with center-pivot irrigation. It is an effective method to reduce or even prevent scouring of sandy soils in windy areas like Oklahoma. The system can effectively irrigate crops with shallow root zones. Its capability of application of insecticides, herbicides, fertilizers, etc. make the system even more versatile.

The method can alleviate heat-stress in the irrigated areas (Chesness and Braud, 1970). This reduction in heat-stress not only reduces air and soil temperatures directly but also attenuates plant water loss from transpiration by raising the atmospheric humidity.

Because of these features--automatic operation, control of application rate and frequency, accommodation to rolling terrain and to sandy soils, improvement in the atmosphere in the irrigated area, and precise application of fertilizers and herbicides--the center-pivot systems are being rapidly adopted throughout the United States, and in some other countries of the world like Libya, Australia, Hungary, France, and the Middle East (Splinter, 1976).

The popularity of the center-pivot system in Oklahoma has been increasing rapidly. Schwab (1971, 1973, 1975, 1977, and 1979) conducted irrigation surveys in Oklahoma and his data indicated a gradually increased tendency of Oklahoma farmers to use center-pivot sprinkler irrigation.

Although the system has been proven to be capable of providing high uniformity of application with nozzles of proper size operating at recommended pressures (Kincaid, 1968) and at recommended spacings (Ali, 1977), Christiansen (1942), Ali (1977), and others have experienced very high evaporation loss, up to 52 percent. Many farmers are not aware that such high loss might occur from the systems, as evidence by the way they are being designed and operated today. With the concept of getting better uniformity of application, the systems are presently operated at high pressures--usually between 414 and 552 kilopascals (kPa) (between 60 and 80 psi). This high operating pressure in conjunction with other system and climatic conditions like riser height, relative humidity, wind speed, air temperature, etc. might lead to increased evaporation loss and decreased uniformity of application. Conservation of water is essential because groundwater reservoirs are being depleted today by the present high rate of use of irrigation water without being replenished.

Sprinkler testing methods have been attempted to follow some standardized procedures (ASAE Recommendations; ASAE R330, 1976, and Ring and Heermann, 1978). To this end, optimum can spacing criterion can be established for the catch can method of sprinkler testing; and the effect of using evaporation suppressant can be investigated and reported.

It is suspected that there exists a relationship of sprinkler evaporation loss with evaporation rate from a U.S. Weather Bureau Evaporation Pan. Such a relationship might help in getting a fairly good estimate of the sprinkler evaporation loss from pan evaporation data without running expensive sprinkler tests in certain localities with known weather data.

It is therefore necessary to study the performance of center-pivot sprinklers with particular emphasis on investigating the evaporation loss as well as the uniformity of application with regard to the various system and climatic factors which influence them and their degree of influence. If the influence of the factors can be quantified, irrigation scheduling can be made accordingly to minimize loss, save energy and water, and achieve satisfactory sprinkler performances.

Scope and Limitations of the Study

The study in this thesis was designed to develop empirical relationships for evaporation loss and uniformity of application of a low trajectory center-pivot sprinkler in regard to the system and climatic variables. This study also attempted to establish criteria for optimum can spacing for a catch can method of sprinkler testing and investigated the effect of using evaporation suppressant in the cans while testing the sprinkler. A study of the relationship between sprinkler loss and pan evaporation loss was also made.

A 7° Trajectory Full Circle Sprinkler was tested under the following levels of the system and climatic variables:

1. Riser height (RHT), two levels:

   Low = 1.52 m (5 ft)

   High = 3.05 m (10 ft)

2. Operating pressures (PRESS), three levels:

   Low = 138 kPa (20 psi)

   Medium = 276 kPa (40 psi)

   High = 414 kPa (60 psi)

3. Relative humidity (RH), two levels:

   Low $\leq$ 55 percent

   High > 55 percent

4. Wind speed (WS), two levels:

   Low < 9.6 kilometers per hour (km/hr) (6 mph)

   High $\geq$ 9.6 km/hr (6 mph)

The stationary distribution pattern obtained from each test was used to determine the evaporation loss, which was considered as the combined loss due to evaporation and drift. The same pattern was used to simulate a continuously moving pattern. The uniformities were calculated using the simulated patterns. Simulation was also done for different sprinkler spacings to study the overlapping of the sprinkler patterns. A relationship between loss and the operating (system and climatic) variables was established using the evaporation loss results. A relationship between uniformity and the operating variables was established using the results of the simulated and overlapped sprinkler patterns. An optimum can spacing criterion was established using the uniformity results at different can spacings of the simulated patterns and effect of evaporation suppressant was studied by conducting nine additional tests using two sets of cans placed at every sampling point, one with kerosene in it and the other without.

Tests at each level of the variables were repeated three times. The following measurements were taken in the field during each test repetition:

1. Flow rate to the sprinkler

2. Operating pressure

3. Relative humidity

4. Wind speed and direction

5. Air temperature

6. Volume of water collected in cans

7. Pan evaporation

8. Flow rate from the field (runoff).

The study was conducted under the following limitations:

1. The tests were conducted with three pressures of 138, 276, and 414 kPa (20, 40, and 60 psi).

2. Two riser heights of 1.52 and 3.05 m (5 ft and 10 ft) were used.

3. The tests were carried out under varying wind speeds ranging from zero km/hr (0 mph) to 21 km/hr (13 mph).

4. The air temperature, T, varied from 19 degrees Centigrade (°C) (66 °F) to 35°C (95°F) during the tests.

5. The relative humidity varied from 34 to 100 percent during the tests.

6. No evaporation suppressant was used in the cans to retard evaporation from them, except in the last nine tests, which were used to study the effect of evaporation suppressant in the cans on evaporation.

7. Only one 7° Trajectory Full Circle Sprinkler was used during the tests with only one nozzle diameter of 0.48 cm (3/16 in.).

Therefore, the results and conclusions of this study are constrained and bounded by the above limitations.

Objectives

The objectives of this study were:

1. To develop empirical relationships for water loss and uniformity of application of a low trajectory center-pivot sprinkler expressed as a function of different factors which influence them.

2. (a) To establish criteria for optimum can spacing of the catch can method of sprinkler uniformity testing.

(b) To investigate the effect of using evaporation suppressant in the catch cans on evaporation while testing a sprinkler.

3. To develop an empirical relationship between sprinkler evaporation loss and pan evaporation loss.

CHAPTER II

REVIEW OF LITERATURE

Loss of water during sprinkling and uniformity of application of water are two major performance characteristics of a sprinkler irrigation system. The loss of water is believed to be dependent on both the sprinkler system parameters such as nozzle size, water pressure, etc., and on the climatic parameters such as air temperature, moisture content of the air, wind velocity, etc. (Clark and Finley, 1975). The uniformity of application depth is largely dependent on the spacing of the sprinklers, wind speed, operating pressure, speed and uniformity of sprinkler rotation, and similar other factors (Christiansen, 1941). The literature reviewed for this thesis covered the above two areas of sprinkler irrigation research.

Loss of Water and Its Dependence

The classical work of Christiansen (1942) has been well recognized by almost all sprinkler irrigation researchers. He investigated spray evaporation loss from a sprinkler irrigation system and reported evaporation using catch can method to range from 10 to 42 percent for afternoon tests; early morning tests had an average of four percent. The researcher made no correlation with climatic variables but reported that losses were high on hot and dry days. This indicated that losses might be highly correlated with evaporative demand of the atmosphere, which, in turn, is dependent upon relative humidity and air temperature.

An extensive study was undertaken by Frost and Schwalen (1955), under Arizona conditions, to determine the percent of water reaching the ground during sprinkling, using the catch can method. No corrections were made for evaporation loss from water collected in the cans during the test period, since in their previous work the correction had appeared to be negligible; this work indicated extremely low application efficiencies at low humidities and high temperatures. However, tests with a single sprinkler, of one to two hour durations, were conducted in daytime and at night, with clear and cloudy weather under various temperatures, humidities, wind conditions, and operating pressures. Spray losses under extreme conditions of bright sunlight at high temperatures and low humidities were reported to range from 35 to 45 percent. From results of their 700 tests conducted under a variety of climatic conditions, they observed that losses increased with temperature, wind speed, operating pressure, and degree of breaking of the spray, and decreased with increase in humidity and nozzle size. Most of their tests were conducted with wind velocities less than 2.2 meters per second (4.92 mph) and some between 3.6 and 4.5 meters per second (8.05 and 10.06 mph). They reported that doubling the wind velocities approximately doubled the losses and stated that losses were considerably higher at high wind velocities.

George (1957) studied spray evaporation losses by determining the salt content of the water in the lateral and in the catchment bottles. Ignoring drift losses, the author reported no correlation between loss and vapor pressure deficit but found a correlation with relative humidity. It was also found that the spray evaporation losses were greater near the sprinkler and near the periphery of the pattern.

In a sprinkler research conducted by Kraus (1966) it was found that the total water loss from the sprinkler system under study ranged from 3.4 to 17.0 percent for relative humidities of 78.4 and 37.0 percent. Results of their water losses agreed very well with those of Frost and Schwalen (1955), indicating that the total water loss varies mainly with parameters pointed out by Frost and Schwalen (1955). Further, Kraus (1955) noted that both the spray evaporation and the total loss were approximately proportional to the relative humidity. He could not establish well defined relationships between loss and wind speed because of lack of full description of the wind conditions.

Seginer (1971) investigated the effect of the application rate on the total water loss during sprinkling. He considered the total loss as the summation of spray evaporation, surface evaporation, and drift loss. From a theoretical analysis based on a simple electrical resistance model of evaporation during sprinkling, he stated that the spray evaporation loss might be negligible relative to the drift loss. He observed that on the average, 36 percent of the total loss occurred due to the drift alone.

Hermsmeier (1973) studied the evaporation from sprinklers in the Imperial Valley of California. He found that air temperature and the application rate were more important factors for estimating sprinkler evaporation than wind velocity or relative humidity. These observations were highly contradictory to those made by Clark and Finley (1975), and many others. In their attempt to determine the water losses from sprinklers, Clark and Finley (1975) conducted a series of tests with a system of 15 sprinklers over an area of 1620 square meters (0.162 ha.). Using catch cans arranged on a 1.5 m grid spacing, they reported that wind velocity and vapor pressure deficit had the most influence on evaporation while operating pressure and air temperature had a minor influence. This result was in partial disagreement with those of Frost and Schwalen (1955) and Hermsmeier (1973), who found little influence of wind speed on evaporation and larger influence from vapor pressure deficit. However, Clark and Finley (1975) observed that below 4.5 meters per second (10.06 mph) of wind, the evaporation losses seem to be random and unrelated to wind velocity; above this velocity, wind speed becomes the controlling factor influencing the evaporation loss and the loss increases exponentially with the wind velocity. Thus the apparent disagreement of the results of Clark and Finley (1975) with those of Frost and Schwalen (1955) and Hermsmeier (1973) was explained. Frost and Schwalen (1975) and Hermsmeier (1973) reported their results from data which were collected when the wind velocities were below the 4.5 meters per second (10.06 mph).

Seginer and Kostrinsky (1975) considered three components of the loss of water between the sprinkler's nozzle and the ground: (1) evaporation loss that occurs in the air and in the catch cans, (2) drift loss that occurs outside the area covered with the cans, and (3) splash loss that occurs from the cans to the outside ground. Assuming that the splash loss can be corrected or checked, one is left with the first two losses which are due mainly to climatic factors. The drift loss presumably is a result of the pressure and wind alone and the evaporation loss is only partially affected by wind. So, for purposes of identifying the sprinkler loss, information of paramount importance to the irrigation farmers, separation of these two loss components does not seem to be necessary. However, on the basis of their study on the data obtained from tests with two single nozzles of 0.40 and 0.50 centimeters (cm) in diameter, Seginer and Kostrinsky (1975) reported that there exists a very high correlation between the loss and the solar radiation while the correlation between loss and wind speed is practically nonexistent. They also noted a very high correlation between solar radiation and relative humidity, indicating that both these variables need not be considered while studying evaporation loss. Their observation that wind speed had little direct effect on water loss was contrary to the results of Wiersma (1955), and Redditt (1969). Giving possible reasons for this discrepancy, Seginer and Kostrinsky (1975) stated that, "Whatever the reason for the discrepancy, there is obviously no one-to-one relationship between total loss and wind speed" (p.254).

Ali (1977) investigated the effect of various systems and climatic conditions on sprinkler loss. Using catch can method with no evaporation suppressant, he reported an average evaporation loss to range from 15 to 35 percent for a 0.726 cm (0.29 in.) diameter spray nozzle, from 40 to 52 percent for a 0.632 cm (0.25 in.) diameter 26° trajectory full circle sprinkler, and from 8 to 41 percent for a 6° trajectory full circle sprinkler having three nozzle sizes of 0.635, 0.559, and 0.483 cm (0.25, 0.22, and 0.19 in.). It was observed that both the relative humidity and the sprinkler type and size had significant effects on evaporation while operating pressure had comparatively little.

Evaporation Suppressant

Many researchers have used the catch can method of sprinkler testing for the purpose of sampling the sprinkler distribution (Frost and Schwalen, 1955; Kraus, 1966; Pair, 1968; Clark and Finley, 1975; Shull and Dylla, 1976; Ring and Heermann, 1978); and many reported that some kind of evaporation suppressant was used in the cans during the tests (Frost and Schwalen, 1955; Pair, 1968; Shull and Dylla, 1976; Ring and Heermann, 1978). The suppressant most commonly used was a light fuel, diesel fuel or kerosene, usually from 5 to 10 milliliters (ml) in each can. These researchers used the suppressant in the cans only to retard or prevent evaporation from the cans, but not much attention has been paid as to the degree of importance and effectiveness in evaporation reduction. Frost and Schwalen (1955) reported from their previous work that the effect of using evaporation suppressant was negligible, but in their present work what they demonstrated graphically indicated that evaporation from cans in the presence of a suppressant was lower than that from cans without it.

Uniformity of Application

The effectiveness of water distributing capability of a sprinkler system is measured in terms of its Uniformity Coefficient, a concept given first by the pioneer sprinkler researchers, Christiansen (1941). He stated:

> To compare sprinkler patterns and to determine how various spacings affect the resulting distribution of water, one needs a numerical expression that can serve as an index of the uniformity secured. For this purpose, I use an expression I call the "Uniformity Coefficient" Cu (p. 90).

He commented that the uniformity of water from sprinklers varies greatly, depending upon pressure, wind, rotation of sprinkler, spacing, and many other factors. He stated that nearly uniform application is possible with proper sprinkler patterns and proper spacing of the sprinklers. Christiansen (1942) defined his uniformity coefficient as:

$$Cu = 100\left[1 - \frac{\Sigma|d - d_{avg}|}{N.\ d_{avg}}\right] \qquad (2.1)$$

where

Cu = uniformity coefficient;

d = depth of water at any grid point;

d_{avg} = average value of d; and

N = total number of grid points (observations).

Since Christiansen's (1942) work, sprinkler irrigation distribution patterns have been characterized by various statistical uniformity coefficients. Wilcox and Swailes (1947) suggested a uniformity coefficient, C_w, as:

$$C_w = 1 - \frac{S}{\bar{Y}} \tag{2.2}$$

where S is the standard deviation of the individual observations, and $\bar{Y}$ is the mean of the observations.

Hart (1961), and Hart and Reynolds (1965) developed a uniformity coefficient, UCH, described as:

$$UCH = 1 - \frac{0.798S}{\bar{Y}} \tag{2.3}$$

where S is the standard deviation of the individual observations, and $\bar{Y}$ is the mean of the observations. This expression was developed on the basis of the assumption that water distribution from commonly used sprinklers, under regular spacing conditions, might be described and approximated by the normal distribution; and the validity of this assumption has been proved by Hart (1961) and Seniwongs et al. (1972), who reported that the distribution of many practical sprinkler systems are normal. Benami and Hore (1964) suggested a uniformity coefficient known as the Benami and Hore uniformity coefficient which is described as:

$$A = 166 \frac{N_a(2T_b + D_bM_b)}{N_b(2T_a + D_aM_a)} \tag{2.4}$$

where

A = Benami and Hore uniformity coefficient;

N_a = number of readings above the overall mean;

N_b = number of readings below the overall mean;

M_a = mean of readings above the overall mean;

M_b = mean of readings below the over all mean;

T_a = sum of readings above M_a;

T_b = sum of readings below M_b;

D_a = difference between the number of readings below and above M_a; and

D_b = difference between the number of readings above and below M_b.

Beale and Howell (1966) compared various uniformity measures and found that linear relationships could be derived which related each of the uniformity measures to each other. Korvan (1968) compared Benami and Hore's (1964) uniformity coefficient to C_u and C_w, and reported that the high degree of correlation among the three uniformity coefficients proved that there is very little difference among them and any of the three uniformity coefficients is acceptable. However, Christiansen's (1942) uniformity coefficient has been recognized by many sprinkler researchers (Chu and Allred, 1968; Heermann and Hein, 1968; Ring and Heermann, 1978; Kelso and Jarrett, 1978; Karmeli, 1978; Solomon, 1979; and many others). Chu and Allred (1968) stated that although laborious, Christiansen's (1942) uniformity coefficient expression can be used to calculate the uniformity of a sprinkler irrigation system if:

1. The spacing of the grid system is small in comparison with the spacing of the sprinkler, and

2. the region of the grid system is clearly specified.

Sprinkler Distribution Patterns

The shape of the sprinkler distribution pattern plays a dominant role in the effectiveness of water distribution from a sprinkler. Acceptable uniformities result from fairly uniform distribution patterns (an absolute uniform application of water is not possible). A pressure that is too low would result in a donut-shaped distribution pattern and a pressure that is too high in an approximately bell-shaped pattern (Pair et al., 1975), none of which would help achieve a fairly uniform distribution, and consequently acceptable uniformities might not be expected from such patterns.

Among climatic factors, wind is probably the principal factors which causes undesirable distribution patterns. Seginer and Kostrinsky (1975), who studied the effect of wind on sprinkler patterns, reported that the only effect of wind was in distorting the distribution patterns.

Shull and Dylla (1976) investigated the effects of wind on application patterns from a large, single nozzle sprinkler. They used a 2.54 cm (1.0 in.) diameter ring nozzle for sprinkling and 9.8 cm (3.86 in.) diameter catch cans, spaced 6.1 m (20 ft) in a square grid pattern. The cans were charged with a small amount of light fuel. From their study on 15 field tests under windy conditions, they found that application pattern distortion was primarily a function of the wind velocity and water pressure. Wind velocity affected their distribution patterns more than did the water pressure. This result was partially supported by Seginer and Kostrinsky (1975) and fully supported by Ali (1977).

Ali (1977) studied the effect of reduced pressure on the performance of center-pivot sprinklers. Using the catch can method he made a qualitative analysis of the effect of wind on distribution patterns and reported that the only effect of wind was pattern distortion. He also observed that at higher application rates, the degree of pattern distortion was larger under windy conditions than in less windy conditions.

Dependence of Uniformity of Application

Although all the uniformity coefficients are reported to be very highly correlated (Korvan, 1968), they are subjected to variability for many reasons. Solomon (1979) pointed out that uniformities are dependent on system variables, namely the sprinkler make, size and type of nozzle, pressure, sprinkler spacing, and the main uncontrollable variable, wind speed. He stated that many factors, other than these five, could affect the outcome of the uniformity test results. The first group of factors involves uncertainties due to experimental method and the second group results from the fact that identical conditions might not be actually identical. Even if all the factors known to influence uniformities would be held constant, some variation in results could be expected, since uniformity determination involves too many measurements that cannot be done precisely.

Effects of pressure, wind variation, and riser height have been reported by Wiersma (1955), considering the uniformity coefficient as the only criterion of sprinkler performance. He reported that riser height had little or no effect on distribution pattern for wind velocities less than 4 mph (6.4 km/hr) and recommended that sprinkler installations be equipped with the tallest riser that can be easily handled by the operator. The researcher also observed little or no difference of pattern coefficients for pressures between 48 and 56 psi (between 331 and 386 kPa) while a slight difference was observed between 30 and 40 psi (between 207 and 276 kPa). He had indications that pressures greater than 56 psi (386 kPa) would be of little value in obtaining better distribution patterns and pressures less than 30 psi (207 kPa) would produce a poorer distribution. He did not report specifically but through his graphs he demonstrated that wind speed reduces uniformity of water distribution irrespective of pressure, sprinkler spacing, and nozzle type and size.

Bilanski and Kidder (1958) conducted an indoor study to investigate the factors that affect the distribution of sprinkler water. They found that the higher the pressure, the more desirable the uniformity. They also observed that the trajectory distance was increased only 5 ft (1.52 m) by raising the pressure from 30 to 60 psi (from 207 to 414 kPa). A significant effect of the angle of inclination of the sprinkler nozzle from the horizontal (trajectory angle) on the distribution of water was reported. They found that as the angle of inclination was increased, the maximum trajectory distance increased and the amount of water deposited at the point of maximum accumulation of water was decreased. As the angle of inclination increased, the rate of decrease was diminished. They stated that the angle of inclination was much more critical at a lower pressure, 20 psi (138 kPa) than it was at a higher pressure. This suggests that there is an optimum trajectory angle which would result in a best possible uniformity of distribution.

The distribution of water by a sprinkler irrigation system is a two-fold phenomenon--the distribution of water from the sprinkler nozzle to the soil and the distribution of water in the soil profile from the soil surface. Pair (1968) conducted research to determine the water distribution from several sprinkler systems. He stated:

> If the application rate of the sprinkler system is less than the infiltration rate of the soil, the water will enter the soil near the spot where it was applied by the sprinkler. If the application rate is greater than the infiltration rate of the soil, runoff occurs and water distribution is poor (p. 648).

The researcher grouped the factors which affect the distribution of water to the soil from the sprinkler system into four groups: (1) management factors which include duration of the system operation, velocity of the sprinkler movement over the ground, alignment of the sprinkler risers with the vertical, and sprinkler machines; (2) climatic factors which include wind speed and direction; (3) sprinkler head factors which include nozzle size, nozzle angle, rotation speed, nozzle pressure, and number and type of nozzles; and (4) distribution system factors which include sprinkler spacing, height and stability of the sprinkler riser, and pressure variation along the sprinkler pipeline. He studied a center-pivot, self-propelled sprinkler system, among others, which had a 453 m (1485 ft) lateral length. Nozzle pressure at the pivot point was 80 psi (552 kPa) and the sprinkler nozzle sizes varied from 1/8 to 1/2 in. (from 0.32 to 1.27 cm) diameters. The speed of the lateral movement was one revolution in 48 hours. From his study on this system, Pair (1968) reported that the system gave good uniformities, between 81 and 86, for wind speeds of 7.1 and 5.0 mph (11.43 and 8.05 km/hr). He observed average application rates to vary from 0.21 in./hr (0.53 cm/hr) at the first tower from the pivot point to 1.01 in./hr (2.57 cm/hr) at the last tower on the outer end of the lateral. The application rate by the larger nozzles was too high to be absorbed by the soil. Since many soils under irrigation today have infiltration rates of less than 0.35 in./hr (0.89 cm/hr), the average application rate of part of his lateral, as he stated, would exceed the infiltration rate of the soil.

The uniformity of application depth with the center-pivot irrigation system is not a function of pressure distribution alone, since pressure distribution can be regulated by increasing the sprinkler size and discharge proportionately to the increase in area as the radial distance from the pivot increases. Heermann and Hein (1968), from their study on a 1300 ft (396.3 m) long self-propelled center-pivot sprinkler irrigation system, reported that the application rate might be too high for many reasons and suggested the following two obvious solutions for this: (1) limit the length of the sprinkler pipeline, or (2) utilize sprinkler heads with longer pattern radius. The longer pattern radius would provide a longer intake opportunity time and allow a reduction in application rate, providing a better uniformity of application depth.

Kincaid and Heermann (1970) studied the pressure distribution on a center-pivot sprinkler irrigation system. From their study on an actual operating system, they developed curves to determine pivot pressure required to maintain a specified minimum pressure at the outer gun. They observed that low pressures resulted in larger drop sizes and reduction in soil intake rate and reported that pipe sizes could be increased and pressure losses decreased on the center-pivot system to reduce pumping cost and improve uniformity of pressure distribution.

The rate and depth of application should conform to the ASAE recommentations (1975) covering minimum requirements for the design, installation, and performance of sprinkler irrigation equipment. One of these recommendations specifies that the application rate should not cause runoff to occur during the normal operation of the sprinkler system. A second is that a uniform distribution of depth of application should be achieved.

CHAPTER III

MATERIALS AND EQUIPMENT

The Sprinkler System

Data for this thesis were collected from a single stationary sprinkler system. The system consisted of a low trajectory sprinkler head, pump, sprinkler pipelines, plastic film covering the entire catchment area, flume, flow meter, and two pressure gages. To obtain data for climatic variables, an anemometer and a sling psychrometer were used. To collect and measure the distribution of water by the sprinkler, 1200 catch cans and six graduated transparent glass cylinders were used. Evaporation from the free water surface was recorded using a U. S. Weather Bureau Evaporation Pan installed in the field. A schematic diagram of the entire system is shown in Figure 1. A view of the system is shown in Figure 2.

Location of the System

The system under study required an adequate and timely supply of water and sufficient area, about 0.33 hectares (ha) (60 m x 55 m), for placing the catch cans to collect all the sprinkler spray. These facilities were available at the Water Conservation Structures Laboratory of the USDA-SEA, 16 km (10 mi) northwest of Stillwater, Oklahoma, and the experimental sprinkler system was located there. In addition to providing the required area, the laboratory had the facility to help prepare

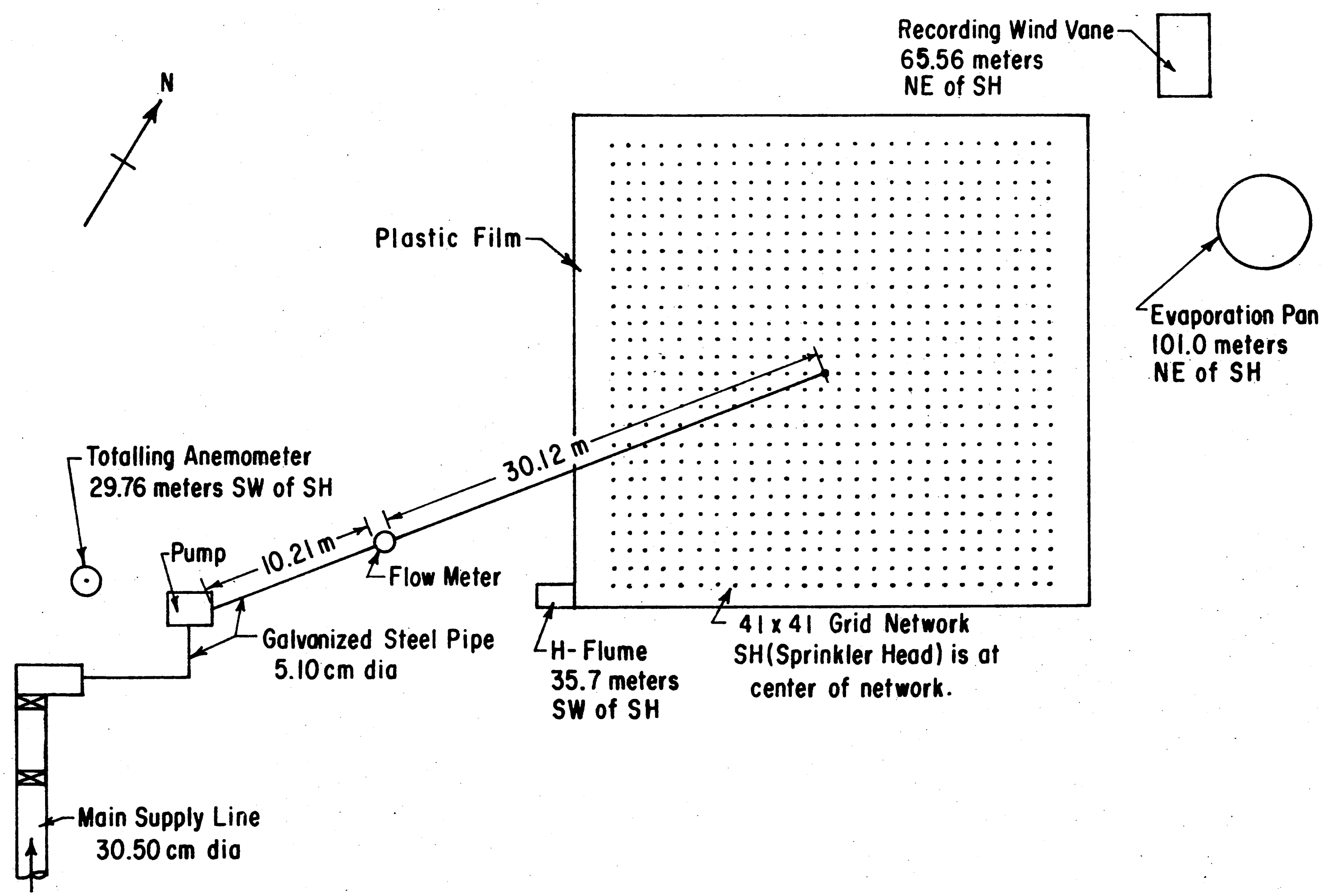

Figure 1. Schematic Diagram of the Sprinkler System

Figure 2. A View of the System

the field and to supply the water to the sprinkler system by gravity flow from the nearby Lake Carl Blackwell through a 30.5 cm (12 in.) diameter main pipeline as and when required.

The Sprinkler Head and the Nozzle

Ali (1977) investigated the effect of reduced pressure on the performance of center-pivot sprinklers and reported that the low trajectory sprinklers offer good promise toward reduced evaporation and satisfactory sprinkler uniformities (>80) as compared to high trajectory sprinklers. Based on this information, it was assumed that farmers would gradually adapt to low trajectory sprinklers in the future for irrigation. Therefore, a 7° Trajectory Full Circle Sprinkler, which had a 7° angle of inclination of the sprinkler barrel with the horizontal was selected for use during the tests. The sprinkler was a Model 4006-1-M manufactured by Senninger Irrigation, Inc. (This and the subsequent information about products do not constitute product endorsements; they are rather stated for clarity.) The 7° Trajectory Full Circle Sprinkler will be designated as 7° LTS in all future references. The sprinkler was tested with a nozzle diameter of 0.48 cm (3/16 in.), since this is a commonly used nozzle size. The sprinkler is shown in Figure 3 at idle condition. Figures 4, 5, 6, and 7 show the sprinkler operating at low pressure-low wind, low pressure-high wind, high pressure-low wind, and high pressure-high wind, respectively.

The Pump

The most common operating pressure of a center-pivot sprinkler system is between 414 and 552 kPa (between 60 and 80 psi). However, this

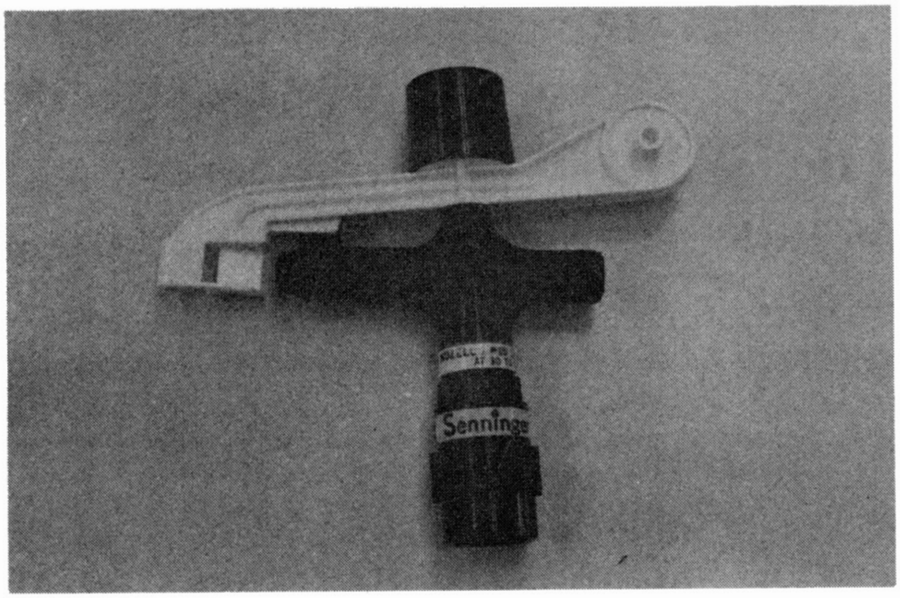

Figure 3. The 7° LTS at Idle Condition

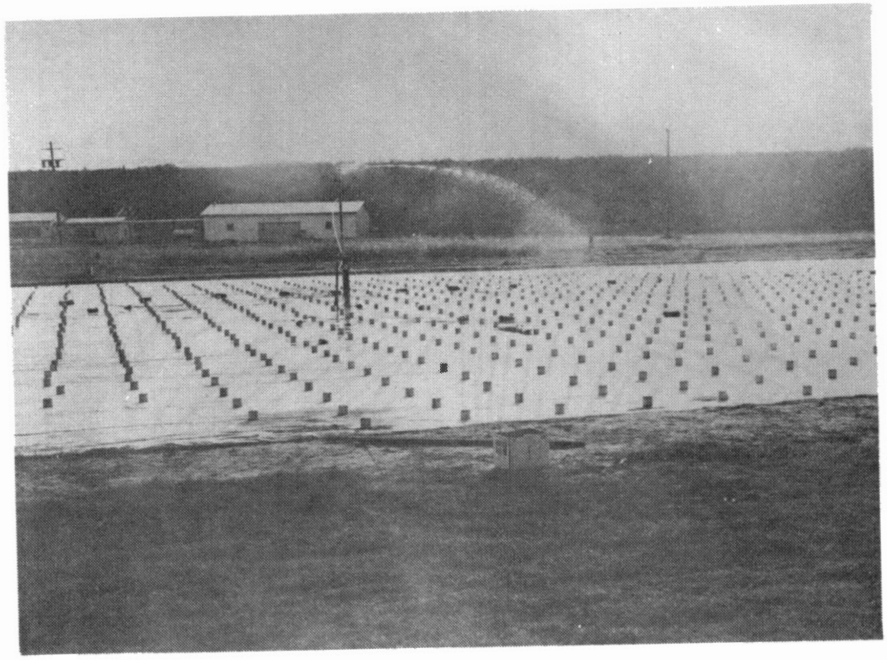

Figure 4. The 7° LTS Operating at Low Pressure-Low Wind

Figure 5. The 7° LTS Operating at Low Pressure-High Wind

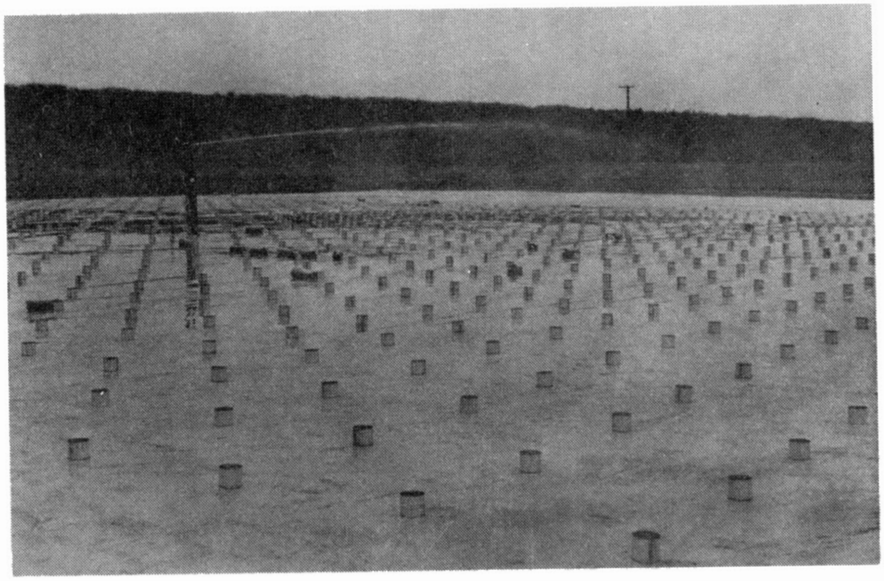

Figure 6. The 7° LTS Operating at High Pressure-Low Wind

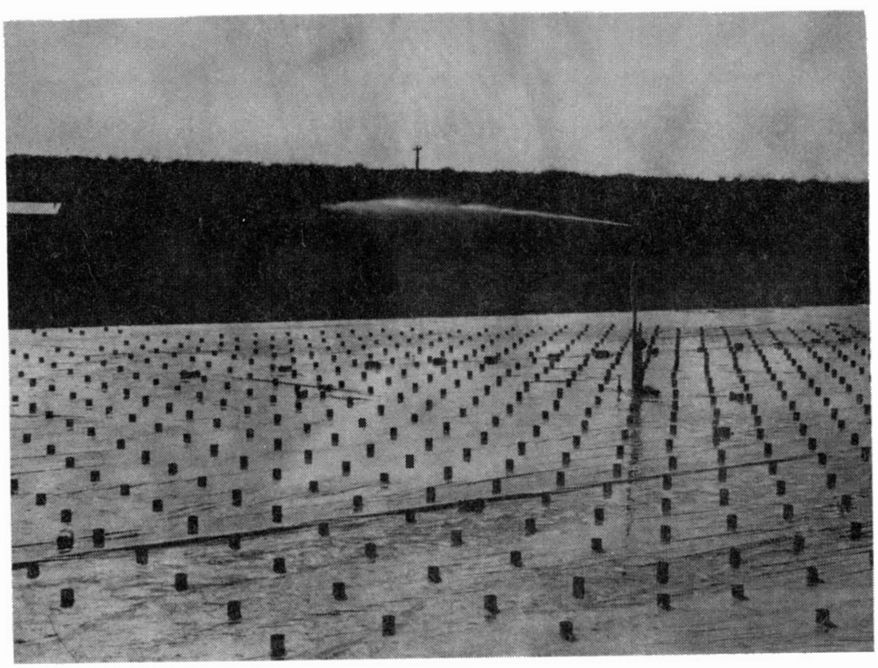

Figure 7. The 7° LTS Operating at High Pressure-High Wind

study was designed to operate a 7° LTS with a 0.48 cm nozzle diameter at a maximum of 414 kPa. In preliminary tests, it was found that the 7° LTS required about 38 liters of water per minute (ℓpm) (10 gpm) when operated at 414 kPa with a 0.48 cm nozzle. A pump was available which could meet the above flow rate and pressure requirements. The pump was a high head-low flow pump and had a pumping capacity of 136 ℓpm (36 gpm) at a maximum pressure of 758 kPa (110 psi). It was a single stage centrifugal Marlow Pump, Model 2-1/2C15S.

Pipelines

The sprinkler system was supplied with water by gravity flow through a 30.5 cm (12 in.) diameter main pipeline. Galvanized steel pipe, 5.08 cm (2.0 in.) nominal diameter, was used to connect the main supply line to the pump, and the pump to the sprinkler risers. Two risers of 3.05 and 1.52 m (10 and 5 ft) were used. The risers were made from the 5.08 cm nominal diameter galvanized steel pipe and were secured, one at a time, at the end of the pipeline to the ground. The 7° LTS was attached at the top of the sprinkler riser.

Plastic Film

To compare the total water loss as determined from the catch can method with the actual loss, it was necessary to catch the total runoff from the sprinkler field. This was achieved by putting a clear plastic sheet over the entire test area. Water that was sprayed from the sprinkler fell on this sheet; a fraction of it was caught by the cans placed on the grid points, and the rest was measured as runoff. The plastic sheet used for this purpose was a clear six ml thick MONSANTO 602 Polyethylene Film purchased from the A. H. Hummert Seed Company of St. Louis, Missouri.

Flume

To measure runoff from the sprinkler field, a flow measuring device was required. The flow measuring device used for this study was an H-flume. In preliminary tests, it was found that the 7° LTS would produce a maximum runoff of about 38 ℓpm (10 gpm) at 414 kPa of pressure. The H-flume selected for this study was capable of measuring 76 ℓpm (20 gpm). The head on the flume was measured using a graduated point gage which could be read to the nearest 0.001 of a foot (0.030 cm).

Flow Meter

To measure the flow rate to the sprinkler system, a 2.54 cm (1 in.) nominal diameter flow meter was installed in the pipeline between the pump and the sprinkler. The flow meter used was a Trident Model 3, capable of recording the total flow in gallons. It could be read to the nearest one-tenth of a gallon (0.38 liters).

Pressure Gages

Bourdon pressure gages were used to measure the pressures during the test. One pressure gage was installed 45.72 cm (1.5 ft) below the sprinkler head and the static pressures at this pressure gage were assumed to be the operating pressures of the sprinkler. A second pressure gage was installed on the pump as a check of the pressure gage at the sprinkler. The pressure gages were connected to the pump and the riser by means of flexible plastic tubing, 0.64 cm (0.25 in.) inside diameter, to avoid any vibrations from the sprinkler system to the pressure gages. The pressure gages could be read to the nearest 6.90 kPa (1.0 psi) and to a maximum of 414 kPa (60 psi).

Anemometer

A cup-type totalling anemometer with three cups was used to determine the wind speed during the test. The anemometer was installed 29.88 m (98 ft) southwest of the sprinkler head at a height of 2.29 m (7.5 ft) above the base of the sprinkler riser.

An eight-direction windvane was used to determine the prevailing wind direction during each test.

Sling Psychrometer

To determine the relative humidity of the surrounding atmosphere during the test period, a sling psychrometer was used to record the dry bulb and web bulb temperatures. The mercury thermometers that recorded the dry bulb and wet bulb temperatures were graduated from 0 to 120°F (-18 to 49°C). Both thermometers could be read to the nearest 1°F.

Catch Cans

The catch can method of sampling the distribution of water was employed in this study. Preliminary tests indicated that the 7° LTS might have a wetted diameter of about 35 m. Therefore, about 1200 catch cans were necessary. These cans were obtained from a food canning industry in Stilwell, Oklahoma. They were No. 3 straight edge squat cans with inside diameters of 10.60 cm (4.17 in.) and heights of 8.53 cm (3.36 in.). The cans were used without lids.

Volume Measuring Cylinders

To measure the volume of water collected in each can in the grid network, two sets of graduated and transparent glass cylinders were used. Each set was comprised of a small cylinder graduated from 0 to 25 ml, a medium cylinder graduated from 0 to 100 ml, and a large cylinder graduated from 0 to 500 ml. The smaller one was used to measure very small amounts of water and could be read to the nearest one ml, the medium one was used for moderate amounts of water and could be read to the nearest one ml, while the large one was used for measuring comparatively large volumes of water and could be read to the nearest five ml.

Evaporation Pan

Records of evaporation from the free water surface were kept using a U.S. Weather Bureau Evaporation Pan. It had an inside diameter of 1.22 m (4 ft) and depth of 0.25 m (10 in.). The pan was constructed and installed following the recommendations of Holtan et al. (1972) and located at 101 m (331 ft) northeast of the sprinkler riser. A 0.20 m (8 in.) high and 0.061 m (2.5 in.) inside diameter stilling well and a point gage were utilized to measure the evaporation from the pan. The point gage used could be read to the nearest 0.001 ft (0.030 cm).

CHAPTER IV

EXPERIMENTAL PROCEDURE

Preparation of the Catchment Area

The field was prepared and equipped in accordance with the ASAE recommendation (1976). The area over which the tests would be conducted was undulating. To create and catch total runoff from the field, grading of the field was necessary. The area was graded to a one percent slope from the north to the south side of the field. A runoff ditch on the southern boundary of the catchment area was graded sloping west at 0.3 percent. Total runoff was measured on the western end of this runoff ditch using the H-flume.

The sprinkler pipelines, flow meter, riser, and the pump were then installed in the field.

Before placing the plastic sheet on the ground, it was necessary to prevent growth of vegetation in the field so that no humps could be created under the plastic sheet which might obstruct the runoff of water. For this purpose, the entire field was treated with chemical herbicides. HYVAR XL produced by DU PONT and ROUNDUP made by MONSANTO were used as herbicides alternatively once every week, for two weeks. The plastic sheet was then placed on the ground, stretching it to avoid any wrinkles that might interfere with the runoff. The edges of the plastic film were buried in the ground to a depth of about 0.15 m (6 in.) to aid against movement.

The next step was to mark a square grid system on the plastic sheet. The size of the square grid was chosen depending on the works of Davis (1966). The researcher investigated the effect of sampling station densities on the properties of the sprinkler system, particularly uniformity of water distribution. He reported that for reasonably uniform distribution patterns, sampling stations representing from 0.25 to 6.67 percent of the pattern area did not affect the different uniformity coefficient values. However, he concluded that for the purpose of identifying the uniformity of water distribution, each sampling station should represent from 2.0 to 2.5 percent of the sprinkler pattern area. Preliminary tests conducted under the present study with the 7° LTS indicated that the sprinkler could have wetted diameters of 20 and 35 m (66 and 115 ft) at 138 and 414 kPa (20 and 60 psi) of pressures, respectively. Therefore, a one-meter square grid system was chosen for this study. This grid size did provide each sampling station (grid point) to represent from 0.32 to 0.10 percent of the pattern area for pressures of 138 and 414 kPa, respectively, which is well within the values indicated by Davis (1966). The largest wetted diameter was 35 m and assuming some pattern elongation might occur in any direction due to wind, a 41 m by 41 m overall grid size was chosen (Figure 1).

Calibration of Equipment

Some of the equipment used for this study had to be calibrated before use. The H-flume and the bourdon pressure gages were calibrated in the Agricultural Engineering Laboratory of Oklahoma State University and the flow meter and the anemometer were calibrated in the field after installation. The flume and the flow meter were calibrated by the time - volume method. The anemometer and the pressure gauges were calibrated with standard pressure gauges. Calibrations were conducted at the beginning and at the end of the sprinkler test program. There were good agreements, within ± 5%, between these two sets of calibration; however, the last calibration results were used to adjust data for this study.

Experimental Plan and Procedure

Group-A Tests

To fulfill the objectives, tests in this study were divided into two groups, Group-A and Group-B. In Group-A tests, different levels of values were assigned to the variables and a test schedule was written combining the variables with their levels, i.e., the schedule was made according to a Factorial Arrangement of tests; the treatments were applied to the experimental unit following a completely randomized design and each treatment (test) was conducted with three repetitions (REPS). Levels were designated by Low (L), Medium (M), and High (H), and for different variables, different range of values were assigned to them as explained in Chapter I. The arrangement of the Group-A tests is shown in Table I. Before each repetition, catch cans were placed on all the grid points of the one-meter square grid network (Figure 1). Volumes of water collected in the cans from the sprinkler were recorded immediately after the test was over. Recording of the volumes required from 30 minutes to one hour for the tests and during this time, volume in cans in the grid network were subjected to evaporation loss. To account for this, 20 test cans were placed in the field with measured amounts of water in them immediately before the termination of the test. Five ml

TABLE I

PLANNING OF GROUP-A TESTS

(3×2^3 Factorial Arrangement in Completely Randomized Design)

RHT	PRESS	WS	RH	REPS
L	L	L	L	3
			H	3
		H	L	3
			H	3
	M	L	L	3
			H	3
		H	L	3
			H	3
	H	L	L	3
			H	3
		H	L	3
			H	3
H	L	L	L	3
			H	3
		H	L	3
			H	3
	M	L	L	3
			H	3
		H	L	3
			H	3
	H	L	L	3
			H	3
		H	L	3
			H	3

of water was used in Can 1, 10 ml in Can 2, 15 ml in Can 3, and so on up to 100 ml in Can 20. When recording of all the can volumes in the grid network was over, these 20 test cans were recorded to adjust the can volumes obtained from the grid network. Can volumes were read using different graduated measuring cylinders. For volumes less than 25 ml, the small cylinder was used while for volumes less than 100 and 500 ml, the medium and the large cylinders were used, respectively.

Frost and Schwalen (1955) stated that they found negligible effect of evaporation suppressant on evaporation from catch cans from one of their early studies; therefore, no suppressant was used in the cans to prevent or retard surface evaporations from the cans.

Group-B Tests

Group-B tests were conducted in a slightly different manner. No variables other than the operating pressure were associated with different levels of values. Three levels of 138, 276, and 414 kPa (20, 40, and 60 psi) were assigned to the operating pressures. Each test was conducted randomly only with the low riser sprinkler (riser height = 1.52 m) and was repeated three times as in Group-A tests. Before each of the nine test repetitions, cans were placed only on the alternate grid points, two cans at each point, of the one-meter square grid network used for Group-A tests. Before every test repetition, one of these two cans was charged with four ml of kerosene and the other can was left empty. Volumes of water collected in each pair of cans were recorded under two separate identities immediately after the test was over. One of the two identities contained records of only 'water data' and the other only 'water plus kerosene' data. With these exceptions, procedures of accounting for evaporation loss during recording of the volumes from the grid network and measuring all the can volumes were similar to those of Group-A tests. The operating conditions of the Group-B tests are shown in Table II.

In addition to recording of the can volumes, records of the test duration, flow of water to the sprinkler, runoff from the sprinkler field, operating pressure of the sprinkler, air temperature, relative humidity, speed and direction of wind, and total evaporation from the evaporation pan were kept for each repetition of the tests. The procedures of recording data for these variables are described below.

Duration of Tests

One of the objectives of the preliminary tests with the 7° LTS was to select a suitable duration of the tests. The test duration was selected such that a measurable amount of water would be collected in all the cans except the ones at the periphery of the sprinkler pattern. A measurable amount of water to fall on these cans would take a very long time which might affect the bulk of the cans in respect to the evaporation loss. From this standpoint, a test duration of 150 minutes was selected for this study. Many researchers (Christiansen, 1941; Frost and Schwalen, 1955; Clark and Finley, 1975) have used test durations of less than 150 minutes.

Determination of Flow of Water to the Sprinkler

Flow of water to the sprinkler was determined using the 2.54 cm flow meter. It recorded the total flow of water in gallons to the sprinkler during the entire test period. To determine the flow rate, readings of the flow meter were taken before and after each test. The

TABLE II

OPERATING CONDITIONS FOR GROUP-B TESTS

TEST NO	PRESS (kPa)	REP #	WS (km/hr)	RH (%)	T (°C)
79	138	1	11.2	27	31
81	138	2	16.0	39	14
85	138	3	9.8	37	20
78	276	1	10.0	33	28
80	276	2	17.4	54	9
86	276	3	5.8	40	22
77	414	1	5.9	27	28
82	414	2	12.7	33	16
87	414	3	7.8	26	27

difference between these two readings when divided by the test duration gave the flow rate in gpm. This flow rate was adjusted using the flow meter calibration equation and then converted to liters per minute for use in the analyses.

Determination of Runoff from the Field

The runoff from the catchment area of the sprinkler was determined using the H-flume. For this purpose, head on the flume was read twice during every test. It was read first near the midpoint of the test when the flow through the flume was first established and for the second time immediately before termination of the test. Using the calibration equation and these two head readings two runoff rates were calculated and averaged to give the runoff rate from the field. Additionally, simultaneous determinations of runoff rates were made from the flume using time-volume method during each of the two head readings. These two runoff rates were again averaged to give a second runoff rate from the field. The runoff rates determined from the flume calibration equation and those from the time - volume method were in good agreement (within ± 5%) under favorable conditions. However, the runoff rates determined by the time-volume method were utilized in the analyses.

Measurement of Pressure

Before opening the flow to the sprinkler, the pressure at the pump, indicated by the pressure gage installed on it, was raised to the desired operating pressure by adjusting the engine rpm to the pump. Flow was then opened to the sprinkler (test started) and the desired static pressure at the sprinkler, indicated by the pressure gage installed on the sprinkler riser, was then set very quickly to the desired operating pressure changing the engine rpm at the pump.

The pressure gages were observed every 15 minutes to check if there was any change in the pressures. If any deviation from the already set desired pressure was observed, it was adjusted immediately to the desired operating pressure.

Measurement of Temperature and Relative Humidity

Three temperatures were recorded during each test, one at the beginning, one at middle, and one at the end of the test. These three temperatures were averaged to give the average temperature during the test. The average temperatures were converted to degree Centigrade for use in the analyses.

A sling psychrometer was used to determine the relative humidity during the test period. Dry bulb and wet bulb temperatures were recorded at the beginning, middle, and end of each test. The dry bulb and the wet bulb temperatures were used with a psychrometric chart, printed by General Electric, to determine the relative humidities at the beginning, middle, and end of the test. The three relative humidity values were averaged to give the average humidity during the test.

Determination of Wind Speed and Direction

Wind speed was recorded using a cup-type totalling anemometer. The anemometer was read at the beginning and end of each test. Difference of these two readings gave the total mileage of wind over the point at which the anemometer was installed. The total mileage when divided by the test duration in hours gave the average wind speed in mph during the test. A one-to-one relationship between the anemometer and a test anemometer was found during calibration of the anemometer. Therefore, values obtained from the anemometer did not need to be corrected. The average wind speed obtained from the anemometer was converted to km/hr for use in the analyses.

The wind direction was recorded using an Eight Direction Belford Windvane installed by the USDA-SEA. Eight directions of North, South, East, West, Northeast, Southeast, Northwest, and Southwest could be read. The wind direction was observed every 15 minutes during the test duration and the most dominant direction was recorded as the prevailing wind direction during the test.

Determination of Evaporation from Evaporation Pan

Evaporation from a free water surface was recorded using the U. S. Weather Bureau Evaporation Pan installed in the vicinity of the sprinkler field. Reading on the pan was recorded once immediately before the test and once at the end of the test for each test repetition. Difference of these two readings gave the total evaporation in ft during the test. The evaporation was converted to cm/hr for use in the analyses.

CHAPTER V

ANALYSES AND DISCUSSIONS

Adjustments of Raw Data

All the sampling cans on the grid network were recorded at the end of each test repetition. This process of recording required considerable time as indicated in Chapter IV. During this time, water in the cans yet to be recorded on the grid network was subjected to evaporation. Data from 20 test cans, placed in the field for this purpose, were used to compensate for this loss. The average loss of water from the 20 cans was assumed to be the loss during the recording process. Catch cans from the grid were read by two persons, always following a particular sequence. The average loss from the test cans was prorated and added to the can volumes of the grid according to this sequence. For example, if the average loss from the test cans was five ml, the first can recorded from the grid was increased by zero (0) ml and the last can by five ml.

In addition, can volumes recorded from the grid were corrected for person-to-person reading variations. The can volumes in the grid were read at the average rate of eight cans per minute. It was suspected that recording of the catch can volumes might be erroneous. This was accounted for by conducting a calibration-type test with 50 cans, each with a different premeasured volume of water. These cans were immediately read by two people--one regular can volume reader and the writer. The regular can volume reader maintained the same speed of about eight cans per minute in reading the cans while the writer took enough time to record the can volumes as correctly as possible. The two sets of readings were utilized to develop a calibration equation which was used to further adjust each individual can reading. Can volumes thus obtained constituted the data suitable for utilizing in the analyses.

Evaporation Loss, EVAP

Seginer (1971) identified various loss components of sprinkler systems as spray evaporation, surface evaporation, and drift. Seginer and Kostrinsky (1975) indicated that separation of the two loss components, spray evaporation and drift, may not be essential for purposes of evaluating sprinkler application loss. This study, in congruence with the above researchers, considered sprinkler application loss as the combined loss of evaporation and drift.

The entire spectrum of the analyses presented in this thesis was based on data from group-A tests, except for the case of determining the effects of suppressant usage on evaporation; group-B test data were utilized for this part of the analyses.

Evaporation of water from spray has been determined using thermodynamic principles by Christiansen (1937). The approximate relationship used for this determination was:

$$E = \frac{100\ c\Delta t}{r}\left[\frac{P_w - P_a}{P_w - P_a - 0.00037\ B\ (t_a - t_w)}\right] \qquad (5.1)$$

where

E = loss of water from the spray (percent);

c = specific heat of water (calories per gram per °F);

r = heat of vaporization (calories per gram);

Δt = drop in temperature of the water from the time it leaves the nozzle until it reaches the ground;

t_w = mean water temperature (°F);

t_a = air temperature (°F);

P_w = vapor pressure of water at temperature t_w (in. of mercury);

P_a = pressure of water vapor in the air (in. of mercury); and

B = barometric pressure (in. of mercury).

However, Kraus (1966), and Clark and Finley (1975) determined evaporation loss using the principle of conservation of mass. In equation form the conservation of mass is:

$$V_{spr} = V_{eva} + V_{fol} + V_{grd} + V_{dft} \tag{5.2}$$

where

V_{spr} = volume of water discharged by the sprinkler (liters [ℓ]);

V_{eva} = volume of water evaporated within the sprinkler pattern (ℓ);

V_{fol} = volume of water retained by foliage within the sprinkler pattern (ℓ);

V_{grd} = volume of water reaching the ground surface (ℓ); and

V_{dft} = volume of water carried by wind as a drift outside the sprinkler pattern (ℓ).

Assuming that the volume of water intercepted by the foliage within the sprinkler pattern causes a reduction in ET (evapotranspiration) equivalent to its magnitude and thus does not constitute a loss, the above equation reduces to:

$$V_{spr} = V_{eva} + V_{dft} + V_{grd} \tag{5.3}$$

Evaporation as defined in this study is the summation of V_{eva} and V_{dft}.

This further reduces Equation (5.3) to:

$$V_{eva} = V_{spr} - V_{grd} \tag{5.4}$$

Using this equation, the amount of evaporation was determined as a percent of loss in relation to the amount applied.

The volume of water applied to the sprinkler is, by continuity, equal to the volume entering the system. The flowrate of the flowmeter when multiplied by the test duration would give the volume entering the sprinkler system. In equation form, this would be:

$$V_{ent} = V_{spr} = (Q_f)\ (T_m) \tag{5.5}$$

where

V_{ent} = volume of water entering the system (ℓ);

Q_f = flowrate at the flowmeter (ℓpm); and

T_m = test duration in minutes.

The volume of water reaching the ground surface was determined using the depth caught by each can placed over every sampling station (grid point) of the 41 by 41 square grid network. These depths when multiplied by the area represented by each sampling station and summed over the entire distribution pattern gave the total volume of water reaching the ground surface.

The depth caught by each can was determined using the relationship:

$$D_{c1}(I,J) = \frac{V_{c1}(I,J)}{A_c} \tag{5.6}$$

where

$D_{c1}(I,J)$ = depth caught by each can spaced one meter apart (cm);

$V_{c1}(I,J)$ = volume caught by each can spaced one meter apart (mℓ);

A_c = interval cross-sectional area of catch cans (sq cm);

I = number of rows in the grid network varying from one to 41; and

J = number of columns in the grid network varying from one to 41.

Total volume reaching the ground surface would then be given by the equation:

$$V_{grd} = \sum_{I=1}^{41} \sum_{J=1}^{41} \frac{D_{c_1}(I,J)(A_g)}{1000} \quad (5.7)$$

where V_{grd} is the total volume of water reaching the ground surface (ℓ), and A_g is the area represented by each sampling station (grid point) (square centimeters [sq cm]). Evaporation loss was then determined by using Equation (5.4) in the following form:

$$EVAP = \frac{V_{spr} - V_{grd}}{V_{spr}} \times 100 \quad (5.8)$$

where EVAP is the evaporation from the sprinkler pattern (percent).

The evaporation analysis was performed on the data obtained from a single stationary sprinkler pattern. A computer program (FORTRAN IV) was written to carry out these calculations for each test repetition. Results of the analysis showed six negative evaporation losses, to the extent of a maximum of -8 percent. Although impossible, this is not surprising. The six negative evaporations resulted from tests which were conducted at low pressure (138 kPa) under very low wind speed (less than 3.7 km/hr) and very high relative humidity (above 87 percent). Evaporation of zero or very close to zero would be expected under such conditions. It was possible that experimental errors associated with such kind of experiments might contribute to errors in favor of reduced evaporation, which resulted in the negative evaporation losses. It could, therefore, be reasonably assumed that the negative evaporations were actually zero or very close to zero percent and the six negative evaporation results were adjusted to zero percent. Evaporation results obtained from the 72 tests ranged from zero to 48 percent for different combinations of the operating conditions. They were in close agreement with the results reported by Frost and Schwalen (1955), and Christiansen (1942). For ease of visualization, the rounded off results of the evaporation analysis were grouped into four groups of evaporation under low wind-low humidity, low wind-high humidity, high wind-low humidity, and high wind-high humidity conditions and are presented in Tables III, IV, V, and VI. An examination of the results indicated that evaporation varied from 20 to 47 percent for low wind-low humidity group tests, from zero to 20 percent for low wind-high humidity group tests, from 29 to 48 percent for high wind-low humidity group tests, and from 13 to 45 percent for high wind-high humidity group tests.

Dependability of the Computed Evaporation Loss

To compare evaporation loss obtained by the procedures described earlier to that determined using the total runoff from the field, the plastic sheet and the H-flume were used. The runoff rate from the field was calculated using the head readings on the flume as described in Chapter IV. The runoff rate when multiplied by the test duration gave the total runoff volume during a test. In equation form, total runoff would be:

$$V_{rof} = (R_{rof})(T_m) \tag{5.9}$$

TABLE III

EVAPORATION RESULTS OF GROUP-A TESTS,
LOW WIND - LOW HUMIDITY TESTS

TEST NO	RHT (m)	PRESS (kPa)	REP (#)	WS (km/hr)	RH (%)	T (°C)	WETDIA (m)	EVAP (%)	PANEVA (cm/hr)
25	1.52	138	1	6.0	52	29	21	22	0.03
63	1.52	138	2	7.3	53	31	20	20	0.07
65	1.52	138	3	9.1	45	29	20	25	0.06
56	1.52	276	1	8.9	48	31	24	36	0.07
62	1.52	276	2	6.6	54	32	24	31	0.05
66	1.52	276	3	6.3	43	30	24	37	0.05
55	1.52	414	1	4.6	48	30	27	35	0.03
61	1.52	414	2	7.9	50	32	26	38	0.07
67	1.52	414	3	6.7	47	29	27	30	0.06
7	3.05	138	1	2.8	52	34	25	25	0.05
44	3.05	138	2	7.9	46	34	23	29	0.07
51	3.05	138	3	7.0	50	32	23	37	0.05
6	3.05	276	1	3.3	52	34	29	40	0.04
9	3.05	276	2	5.5	55	33	28	39	0.03
10	3.05	276	3	3.0	46	34	29	36	0.05
11	3.05	414	1	9.3	54	34	27	47	0.07
54	3.05	414	2	6.0	42	31	30	36	0.03
52	3.05	414	3	6.0	54	32	28	43	0.03

TABLE IV

EVAPORATION RESULTS OF GROUP-A TESTS, LOW WIND - HIGH HUMIDITY TESTS

TEST NO	RHT (m)	PRESS (kPa)	REP (#)	WS (km/hr)	RH (%)	T (°C)	WETDIA (m)	EVAP (%)	PANEVA (cm/hr)
26	1.52	138	1	0.0	93	19	23	0	0.00
29	1.52	138	2	2.1	92	23	22	0	0.01
31	1.52	138	3	1.3	93	20	23	0	0.00
22	1.52	276	1	0.1	95	19	28	3	0.00
23	1.52	276	2	4.5	76	22	26	12	0.01
30	1.52	276	3	3.7	92	24	27	5	0.00
27	1.52	414	1	5.2	79	25	30	13	0.01
32	1.52	414	2	2.1	89	23	30	8	0.01
33	1.52	414	3	1.6	89	21	31	7	0.00
12	3.05	138	1	0.7	89	21	26	0	0.00
41	3.05	138	2	1.3	87	24	25	0	0.00
45	3.05	138	3	3.7	86	23	24	0	0.00
5	3.05	276	1	5.1	90	24	29	13	0.00
13	3.05	276	2	4.3	81	25	30	16	0.01
18	3.05	276	3	3.2	84	27	31	16	0.00
4	3.05	414	1	3.9	100	21	33	10	0.01
16	3.05	414	2	1.5	83	23	34	11	0.01
34	3.05	414	3	3.2	80	24	31	20	0.00

TABLE V

EVAPORATION RESULTS OF GROUP-A TESTS,
HIGH WIND - LOW HUMIDITY TESTS

TEST NO	RHT (m)	PRESS (kPa)	REP (#)	WS (km/hr)	RH (%)	T (°C)	WETDIA (m)	EVAP (%)	PANEVA (cm/hr)
69	1.52	138	1	21.1	44	24	18	36	0.05
73	1.52	138	2	10.2	45	30	20	29	0.06
74	1.52	138	3	11.2	40	31	19	33	0.08
64	1.52	276	1	10.9	44	29	23	38	0.05
70	1.52	276	2	19.6	36	25	21	41	0.07
71	1.52	276	3	9.6	34	29	24	44	0.06
57	1.52	414	1	12.6	47	34	24	41	0.08
72	1.52	414	2	11.6	44	25	25	37	0.06
76	1.52	414	3	14.0	52	27	24	36	0.02
39	3.05	138	1	11.3	42	35	22	48	0.07
43	3.05	138	2	11.7	41	34	22	46	0.08
53	3.05	138	3	13.2	43	31	21	45	0.06
38	3.05	276	1	10.9	54	33	26	38	0.03
42	3.05	276	2	10.6	51	33	25	46	0.04
46	3.05	276	3	12.2	45	33	25	47	0.09
40	3.05	414	1	10.6	40	35	27	41	0.08
47	3.05	414	2	10.8	43	33	28	39	0.07
49	3.05	414	3	9.9	53	32	27	36	0.08

TABLE VI

EVAPORATION RESULTS OF GROUP-A TESTS,
HIGH WIND - HIGH HUMIDITY TESTS

TEST NO	RHT (m)	PRESS (kPa)	REP (#)	WS (km/hr)	RH (%)	T (°C)	WETDIA (m)	EVAP (%)	PANEVA (cm/hr)
60	1.52	138	1	12.2	59	33	20	23	0.07
83	1.52	138	2	19.2	68	24	19	32	0.02
88	1.52	138	3	16.5	60	28	19	31	0.05
58	1.52	276	1	14.5	66	30	23	27	0.02
68	1.52	276	2	16.5	64	19	22	23	0.01
75	1.52	276	3	10.7	72	21	23	16	0.01
59	1.52	414	1	15.2	57	33	23	39	0.06
89	1.52	414	2	15.7	70	29	23	34	0.04
90	1.52	414	3	19.6	71	27	23	33	0.03
1	3.05	138	1	13.8	74	26	24	13	0.02
3	3.05	138	2	15.6	63	34	22	45	0.06
8	3.05	138	3	12.2	65	28	23	28	0.03
2	3.05	276	1	14.5	72	30	25	31	0.02
91	3.05	276	2	10.9	71	28	26	24	0.03
92	3.05	276	3	11.2	73	29	26	32	0.04
14	3.05	414	1	12.7	63	32	27	41	0.04
50	3.05	414	2	9.7	67	26	27	35	0.01
93	3.05	414	3	9.8	76	27	27	27	0.01

where V_{rof} is the total volume of runoff (ℓ), and R_{rof} is the rate of runoff (ℓpm).

Evaporation loss using runoff data was computed utilizing results from Equation (5.5) into the following relationship:

$$EVAFLM = \frac{V_{spr} - V_{rof}}{V_{spr}} \times 100 \qquad (5.10)$$

where EVAFLM is evaporation from the sprinkler pattern at the flume (percent), and V_{spr} is volume of water discharged by the sprinklers (ℓ).

Tests conducted only under low wind and high humidity conditions could be used for the comparison, since conditions otherwise would impose significant evaporative demand on runoff. It was assumed that under low wind and high humidity conditions negligible evaporation would occur on runoff from the field to the flume. Leakage through the plastic sheet was another deterrent factor in choosing the tests to be used for comparison. A false loss would be indicated by the flume under a test conducted with leaky plastic. Six tests were available for comparison with low wind-high humidity conditions and no leakage through the plastic. Rounded off evaporation results of these tests are shown in Table VII. A comparison between the evaporation loss using the flume (EVAFLM) and that using the catch can method (EVAP) was made utilizing the Student's t-test. A t-value of 1.89 was observed and the probability of a larger t was computed as 0.1176, which was insignificant with a five percent α-risk. This indicated that there was not any significant difference between the two losses compared. In other words, losses computed by the catch can method were comparable to those determined using the flume, which were assumed to be very close to the actual losses.

TABLE VII

COMPARISON OF EVAPORATION COMPUTED FROM TOTAL RUNOFF (EVAFLM) AND THAT FROM USING CATCH CAN METHOD (EVAP)

TEST NO	RHT (m)	PRESS (kPa)	WS (km/hr)	RH (%)	T (°C)	EVAP (%)	EVAFLM (%)	EVAFLM-EVAP
24	1.52	276	6.9	57	27	25.5	26.2	0.73
23	1.52	276	4.5	76	22	11.5	11.6	0.04
27	1.52	414	5.2	79	25	13.3	13.4	0.09
13	3.05	276	4.3	81	25	16.0	16.4	0.34
20	1.52	414	8.4	86	24	14.1	16.5	2.41
22	1.52	276	0.1	95	19	3.0	3.5	0.48

Evaporation Model in Original Variables

Results of the evaporation analysis were utilized to develop an empirical model relating evaporation loss as a function of the different evaporation controlling variables. Five variables that were considered to influence evaporation were relative humidity (RH), air temperature (T), wind speed (WS), riser height (RHT), and operating pressure (PRESS). SAS (Statistical Analysis System) packages were available through the Oklahoma State University Computer Center by means of which different regression techniques could be explored to develop this and the subsequent models in this study.

The Stepwise Regression, Forward Selection, Backward Elimination, R-Square Improvement and GLM (General Linear Model) techniques were performed with the above named five independent variables and the dependent variable, evaporation loss. All the techniques gave about the same type of results. However, results from the Stepwise and Least Square Regression procedures were summarized and are presented in Table VIII. An examination of the results revealed that the best single independent variable was RH, which alone could explain 72 percent of the variation about the mean in the data. This one variable model was associated with a standard deviation, s, of 7.47, and an F value of 0.0001 with an α-risk of five percent. The highly significant F value indicated that this one variable model was adequate, i.e., was useful in predicting evaporation loss.

On the other hand, the high standard deviation value suggested that improvement of the model might be possible, i.e., a better fit to the data might be achievable. Draper and Smith (1966) narrate criteria of examining a regression equation. The criteria of a better fit are that:

TABLE VIII

SUMMARY OF REGRESSION PROCEDURES OF EVAPORATION MODEL:
ORIGINAL VARIABLES

REGRESSION PROCEDURES FOR DEPENDENT VARIABLE EVAP

NUMBER IN MODEL	R-SQUARE	VARIABLES IN MODEL	CV, %	s, %	PROB > F
1	0.72	RH	27	7.47	0.0001
2	0.78	RH T	24	6.68	0.0001
3	0.85	WS RH T	20	5.62	0.0001
4	0.89	PRESS WS RH T	17	4.76	0.0001
5	0.91	RHT PRESS WS RH T	16	4.42	0.0001

The variables in the above model have all been deemed significant at the 0.1000 significance level

(1) the square of the multiple correlation coefficient, R^2, should be higher; (2) the standard error of estimate or the standard deviation, s, should be smaller; (3) the standard error of estimate as a percent of the mean response, i.e., the coefficient of variation, CV, should be smaller; and (4) the sequential and partial F statistics should be significant. Among these, the statistic s is probably most important, since when s becomes very small, all other criteria tend to be satisfied. The value of s can be decreased by increasing the number of independent variables in the model, or by providing an appropriate nonlinear polynomial fit to the data. Table VIII shows that when the number of variables in the model was increased, the s value decreased and the R^2 value increased (reduction in residual sum of square) leading to apparently gradual better models. The regression models resulting from the use of the regression techniques are presented below. All of these models had highly significant F values and were deemed adequate.

1. One variable "best" model:

$$EVAP = 69.27 - 0.67\ RH \tag{5.11}$$

(R^2 = 0.72, CV = 27 percent, s = 7.47 percent)

2. Two variable "best" model:

$$EVAP = 25.03 - 0.46\ RH + 1.10\ T \tag{5.12}$$

(R^2 = 0.78, CV = 24 percent, s = 6.68 percent)

3. Three variable "best" model:

$$EVAP = 5.80 - 0.32\ RH + 1.23\ T + 0.80\ WS \tag{5.13}$$

(R^2 = 0.85, CV = 20 percent, s = 5.62 percent)

4. Four variable "best" model:

$$EVAP = 1.45 - 0.34\ RH + 1.16\ T + 0.81\ WS + 0.03\ PRESS \quad (5.14)$$

(R^2 = 0.89, CV = 17 percent, s = 4.76 percent)

5. Five variable "best" model:

$$EVAP = 7.95 - 0.40\ RH + 0.83\ T + 0.85\ WS + 0.03\ PRESS + 2.71\ RHT \quad (5.15)$$

(R^2 = 0.91, CV = 16 percent, s = 4.42 percent)

where

EVAP = evaporation loss (percent);

RH = relative humidity (percent);

T = air temperature (°C);

WS = wind speed (km/hr);

PRESS = operating pressure (kPa); and

RHT = riser height (m).

Table VIII shows that reduction in s value and increment in R^2 value practically ceased at the five variable model, indicating that the four variable model was as good as the five variable model in predicting evaporation loss. Therefore, for further analysis, the four variable model was selected. The analysis of variances associated with this model is presented in Table IX and those associated with the other four models are presented in Appendix A.

To justify adequacy or correctness of a model, examination of the residuals is a very useful tool. Residuals are the differences between what is actually observed and what is predicted by the regression equation--that is, the amount which the regression equation has not been able to explain. In performing regression analysis, certain assumptions about

TABLE IX

ANALYSIS OF VARIANCE OF THE EVAPORATION MODEL:
ORIGINAL VARIABLES

STATISTICAL ANALYSIS SYSTEM
ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE EVAP

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F	R-SQUARE	C.V.
REGRESSION	4	12534.73819437	3133.68454859	138.03339	0.0001	0.89178425	17.19767 %
ERROR	67	1521.05853363	22.70236617			STD DEV	EVAP MEAN
CORRECTED TOTAL	71	14055.79672800				4.76470001	27.70530

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB>F	PARTIAL SS	F VALUE	PROB>F
RH	1	10153.69880606	447.25289	0.0001	943.41982643	41.55601	0.0001
T	1	822.92208305	36.24830	0.0001	901.99179938	39.73118	0.0001
WS	1	934.78964264	41.17587	0.0001	949.79280159	41.83673	0.0001
PRESS	1	623.32766261	27.45651	0.0001	923.32766261	27.45651	0.0001

SOURCE	B VALUES	T FOR H0:B=0	PROB>|T|	STD ERR B	STD B VALUES
INTERCEPT	1.44979125	0.17600	0.8608	8.23743992	0.0
RH	-0.33533784	-6.44640	0.0001	0.05201943	-0.42624920
T	1.16247552	6.30327	0.0001	0.18442427	0.38320129
WS	0.80552479	6.46813	0.0001	0.12453747	0.29755350
PRESS	0.02620907	5.23990	0.0001	0.00500183	0.21120719

the residual errors are made (Draper and Smith, 1966); the usual assumptions are that the errors are independent, have zero mean, a constant variance, and follow a normal distribution. Thus, if the fitted model is correct, the residuals should exhibit tendencies to conform to the assumptions, or at least should not exhibit a denial of the assumptions. Graphical procedures of examining the residuals were employed. Plots of residuals against each variable in the model and the values predicted by the model were examined visually to check the model. To conform to or not to deny the assumptions, the residual plots should not exhibit any discernible patterns other than a horizontal band (Draper and Smith, 1966). For the four variable model, no denials were noted from any of the residual plots shown in Figures 8 through 12, indicating that the model was adequate and no assumptions were violated. Good agreement, within -10 and +8 percent, between observed and predicted values were observed, indicating the acceptability of the model for predictive purposes. The agreement is reflected by Figure 13, which is a plot of the predicted evaporation loss versus observed loss. Under ideal conditions, these two sets of values should fall on a straight line, 45° to the horizontal. Figure 13 did not disprove this trend.

The regressions summary (Table VIII) and the analysis of variance for the four variable model (Table IX) indicated another important aspect of the analysis, the degree of importance of the independent variables on EVAP. The tables suggested that RH, T, WS, and PRESS were the variables, respectively, in order of descending importance for evaporation estimation, i.e., RH had the most influence and PRESS the least, on sprinkler evaporation loss. This order suggests that loss from sprinklers could be minimized if the sprinkler systems are operated during calm and mild

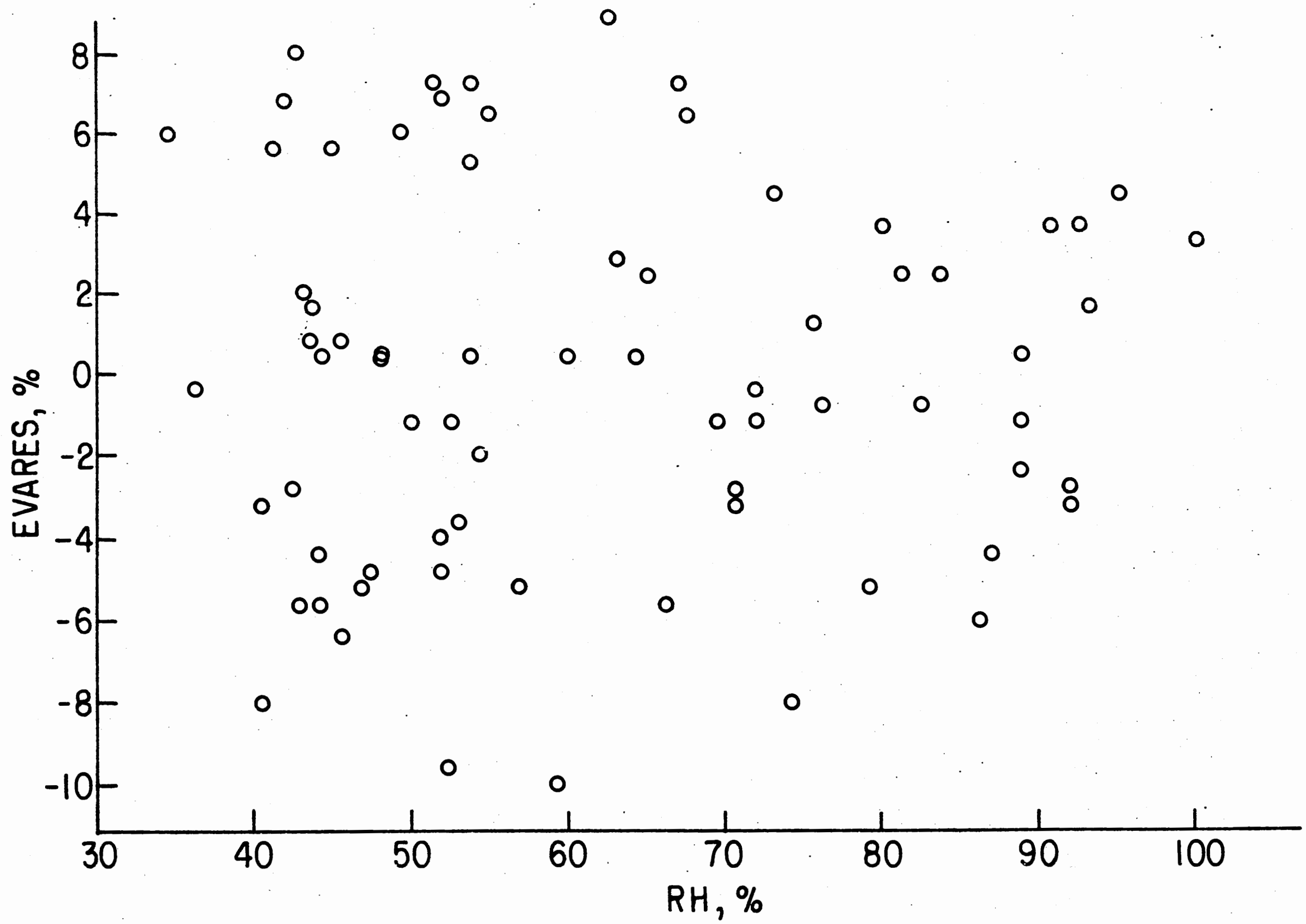

Figure 8. Plot of Residual, EVARES Versus Relative Humidity, RH

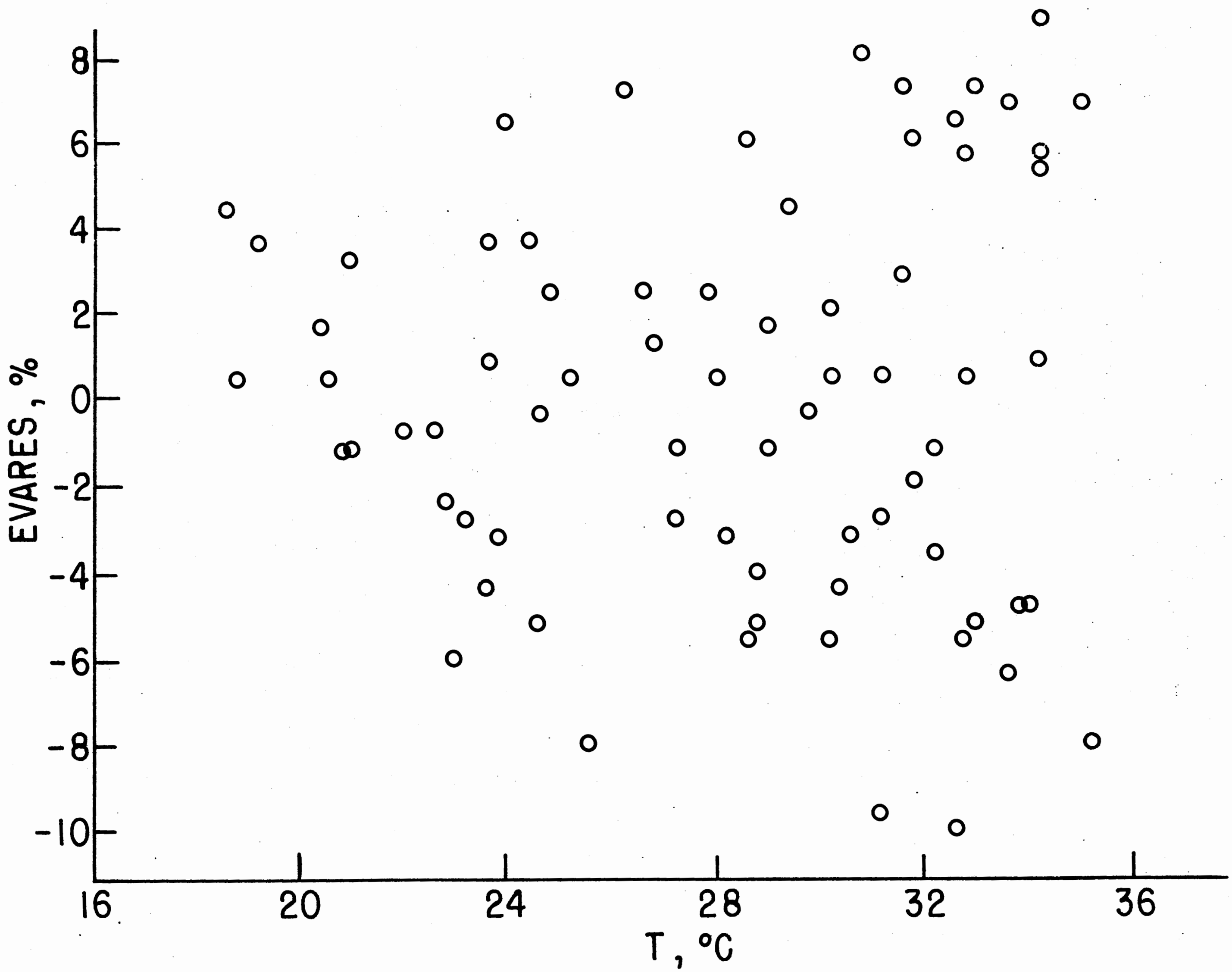

Figure 9. Plot of Residual, EVARES Versus Temperature, T

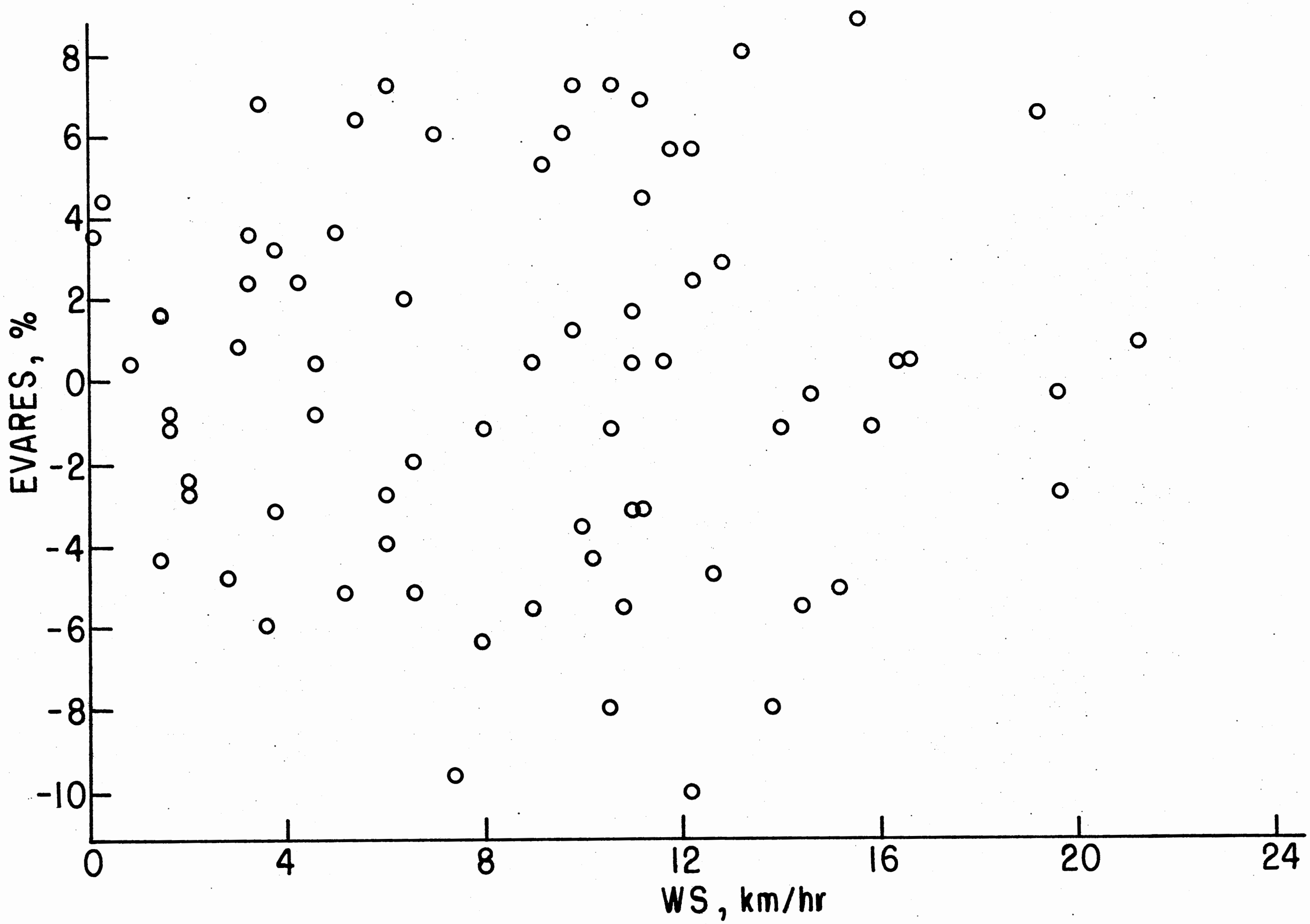

Figure 10. Plot of Residual, EVARES Versus Wind Speed, WS

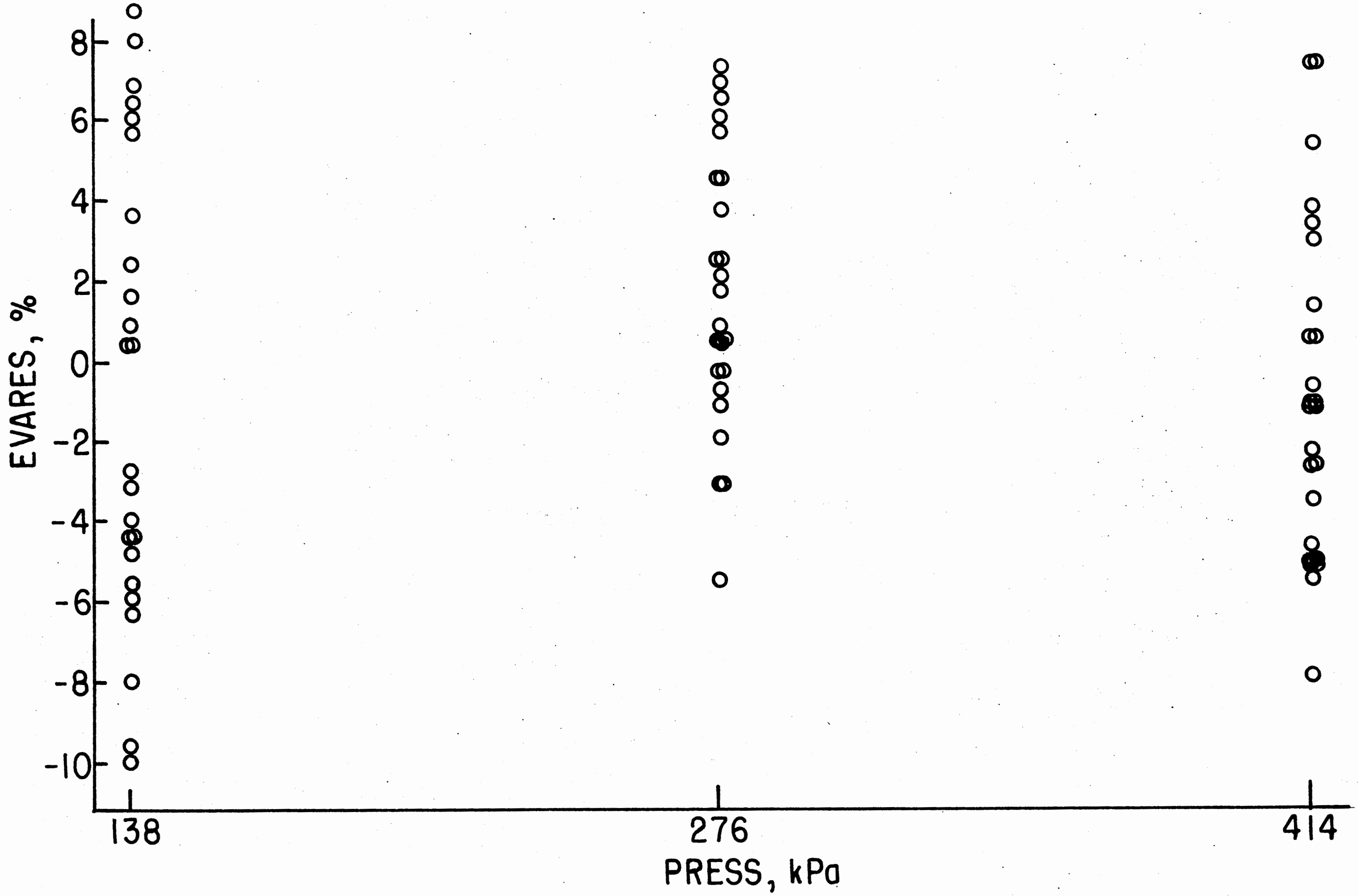

Figure 11. Plot of Residual, EVARES Versus Pressure, PRESS

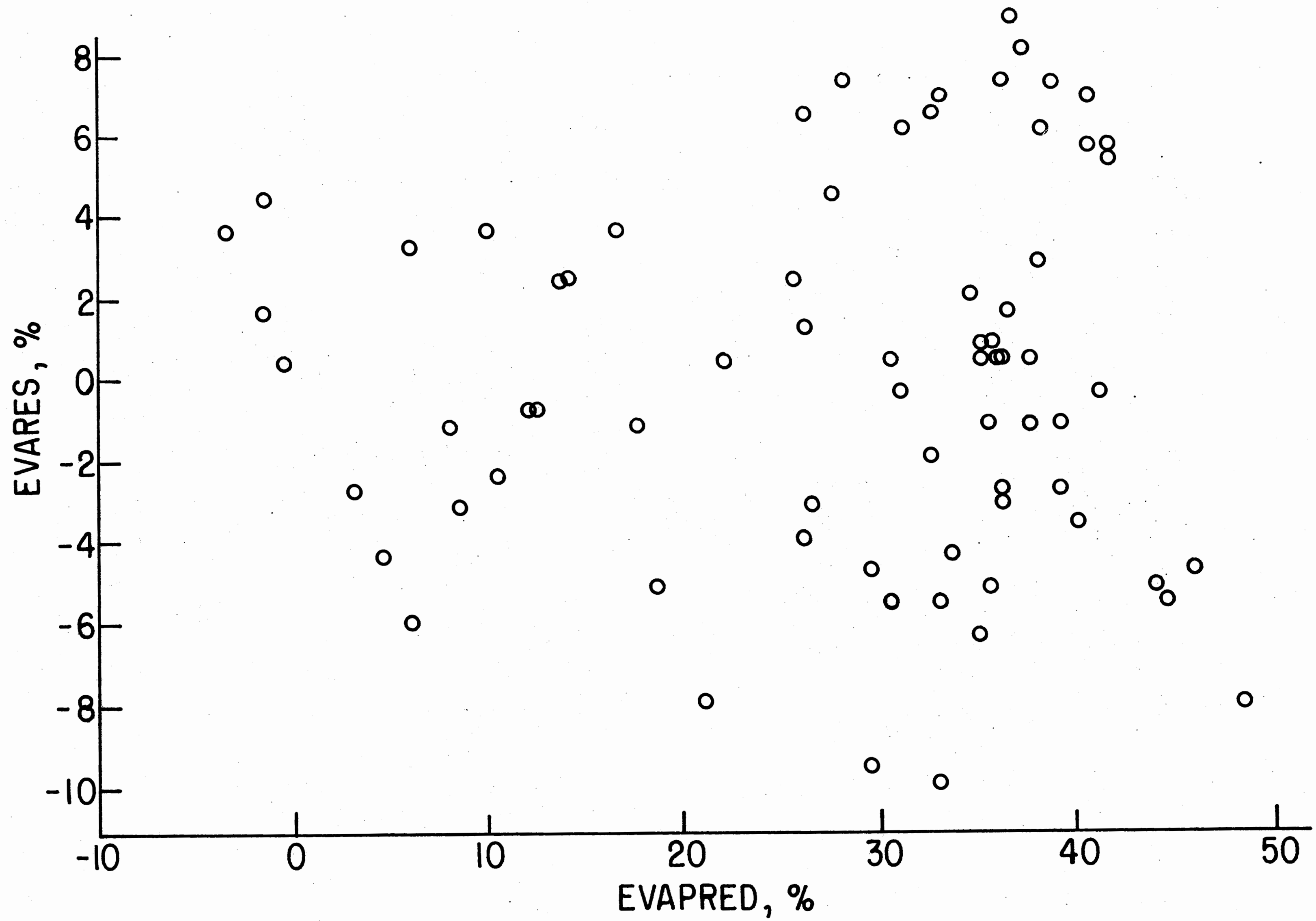

Figure 12. Plot of Residual, EVARES Versus Predicted Evaporation, EVAPRED

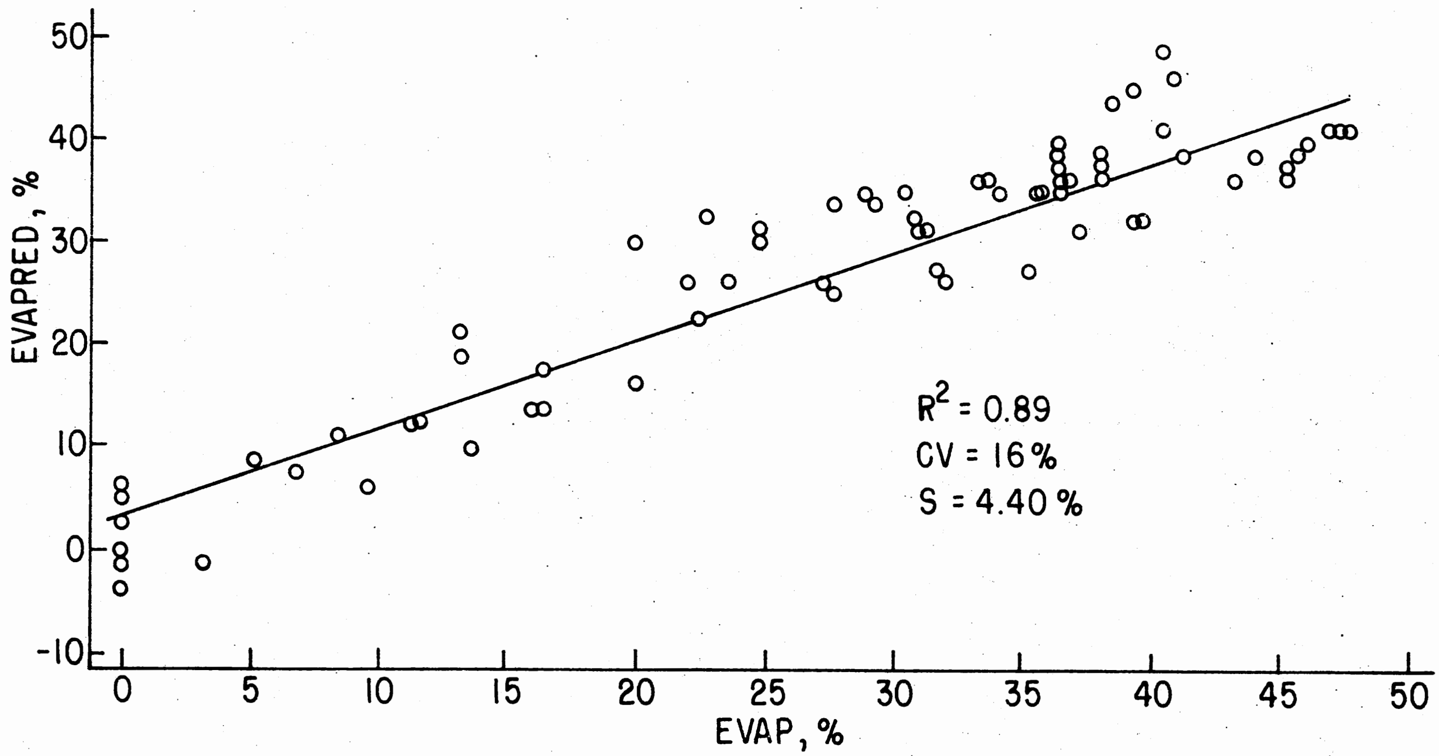

Figure 13. Plot of Predicted Evaporation, EVAPRED Versus Observed Evaporation, EVAP

hours of the day. The four variable evaporation model showed that losses increased with increase in T, WS, and PRESS and with a decrease in RH; similar observations on loss were reported by Frost and Schwalen (1955), Clark and Finley (1975), and many others.

Evaporation Model Using Transformation of the Original Variables

Although the analysis so far resulted in an adequate evaporation model, the question still remained, "Was there any further improvement of the model possible?" This question led to attempts seeking some better models using suitable transformations of the variables. The purpose of making transformations of the variables was to be able to find a regression model of linear form in the transformed variables, rather than a more complicated nonlinear one in the original variables.

Some of the values of the variables, EVAP and WS, were either zero or adjusted to zero for reasons explained earlier. Transformation of these data were not possible unless they were adjusted to non-zero values. Therefore, the zero values of the population of EVAP and WS data were arbitrarily assigned a value extremely close to zero, so that quantitatively the data were not affected. Whatever change the data suffered by this assignment was very insignificant to facilitate suitable transformations only. To this end, the zero percent EVAP was readjusted to a 0.001 percent loss and the zero km/hr of WS was adjusted to a 0.001 km/hr.

Several transformations involving logarithmic, exponential, square and square root transformation, and all possible combinations of the cross products were utilized. The stepwise regression, forward selection, backward elimination, and the R-square improvement techniques were employed as before on the transformed data. Examination of the results showed that the transformed data provided some apparently better models as compared to the models in the original data. The dependent variable EVAP, when transformed to a square root function ($\sqrt{EVAP}$ = YEVA4), was explained better by the data with transformed variables. With this square root transformation of the dependent variable, all regression techniques gave about the same results. However, results from the stepwise and least square regression procedures were summarized and are presented in Table X. It shows that all five models were able to adequately describe the data, and the s and CV values were significantly reduced, even with the one variable as compared to Table IX. The s value reduced from 7.47 to 1.02 and the CV from 27 to 21 percent. The five regression models resulting from the analysis with transformed data are shown below:

1. One variable "best" model:

$$EVAP = (7.73 - 0.00067\ RH^2)^{\frac{1}{2}} \qquad (5.16)$$

(R^2 = 0.71, CV = 21 percent, s = 1.02 percent)

2. Two variable "best" model:

$$EVAP = (1.15 - 0.00067\ RH^2 + 2.74\ \text{Log}\ (PRESS))^{\frac{1}{2}} \qquad (5.17)$$

(R^2 = 0.80, CV = 18 percent, s = 0.87 percent)

3. Three variable "best" model:

$$EVAP = (-0.95 - 0.00052\ RH^2 + 2.66\ \text{Log}\ (PRESS) + 0.60\sqrt{WS})^{\frac{1}{2}} \qquad (5.18)$$

(R^2 = 0.86, CV = 15 percent, s = 0.73 percent)

4. Four variable "best" model:

$$EVAP = (-3.37 - 0.00034\ RH^2 + 2.58\ \text{Log}\ (PRESS)$$

TABLE X

SUMMARY OF REGRESSION PROCEDURES OF EVAPORATION MODEL: TRANSFORMED VARIABLES

REGRESSION PROCEDURES FOR DEPENDENT VARIABLE YEVA4

NUMBER IN MODEL	R-SQUARE	VARIABLES IN MODEL	CV, %	s, %	PROB > F
1	0.71	X13	21	1.02	0.0001
2	0.80	X2 X13	18	0.87	0.0001
3	0.86	X2 X9 X13	15	0.73	0.0001
4	0.89	X2 X9 X13 X18	13	0.64	0.0001
5	0.90	RHT X2 X9 X13 X18	13	0.62	0.0001
6	0.91	RHT X2 X4 X9 X13 X18	12	0.61	0.0001

The variables in the above model have all been deemed significant at the 0.1000 significance level

$$+ 0.66\ WS + 0.0021\ T^2)^{1/2} \quad (5.19)$$

$(R^2 = 0.89$, CV = 13 percent, s = 0.64 percent)

5. Five variable "best" model:

$$EVAP = (-3.33 - 0.00039\ RH^2 + 2.60\ \text{Log}\ (PRESS) + 0.66\sqrt{WS} + 0.0015\ T^2 + 0.26\ RHT)^{1/2} \quad (5.20)$$

$(R^2 = 0.90$, CV = 13 percent, s = 0.62 percent)

Table X suggests that the four variable model is equivalent to the five variable model in predicting evaporation loss. Therefore, the four variable model was considered as a competitive one to the model already developed in the original variables. The analysis of variance associated with this model is shown in Table XI and those associated with the other four models in transformed variables are shown in Appendix B.

It would be misleading to describe the adequacy of the model just by looking at the smaller values of CV and s. This probably resulted from the transformation of variables. With smaller CV and s values, the residuals should not display any anomalies as well. The residual plots of the transformed-variables model, shown in Appendix E, exhibited denials of the assumptions of regression. Therefore, this model could not be considered superior to the model in original variables. Thus, considering the different statistics and regression assumptions, the four variable model in original variables shown below was considered as a satisfactory, adequate, and acceptable evaporation model.

$$EVAP = 1.45 - 0.34\ RH + 1.16\ T + 0.81\ WS + 0.03\ PRESS \quad (5.14)$$

Sprinkler Distribution Patterns

The shape of the sprinkler distribution patterns dictates sprinkler

TABLE XI

ANALYSIS OF VARIANCE OF THE EVAPORATION MODEL:
TRANSFORMED VARIABLES

STATISTICAL ANALYSIS SYSTEM

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE YEVA4

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F	R-SQUARE	C.V.
REGRESSION	4	227.74087866	56.93531965	138.25728	0.0001	0.89194056	13.05585%
ERROR	67	27.59102286	0.41180631			STD DEV	YEVA4 MEAN
CORRECTED TOTAL	71	225.33190152				0.64172137	4.91520

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB>F	PARTIAL SS	F VALUE	PROB>F
X13	1	182.19794913	442.43603	0.0001	14.89216913	36.16304	0.0001
X2	1	21.04180127	51.09635	0.0001	18.43115716	44.87828	0.0001
X9	1	16.10884241	39.11752	0.0001	19.06549178	46.29723	0.0001
X18	1	8.39228584	20.37921	0.0001	8.39228584	20.37921	0.0001

SOURCE	B VALUES	T FOR H0:B=0	PROB>|T|	STD ERR B	STD B VALUES
INTERCEPT	-3.37375035	-2.99306	0.0039	1.12719287	0.0
X13	-0.00034185	-6.01357	0.0001	0.00005685	-0.42933588
X2	2.57654259	6.69912	0.0001	0.38460883	0.26953278
X9	0.65591809	6.80421	0.0001	0.09639891	0.34468625
X18	0.00208427	4.51433	0.0001	0.00046170	0.27920553

uniformities. Smooth and uniform shaped patterns would result in higher uniformities and irregular or distorted shaped patterns in poorer uniformities. Pressure and wind speed are believed to be the dominating factors controlling the shape of distribution patterns (Christiansen, 1937; Pair et al., 1975; Shull and Dylla, 1976).

Distribution patterns have been described using two-dimensional graphical procedures. Distribution depths from a single sprinkler head have been utilized to draw distribution-depth contours. Visualization of the shape from these contours is not impossible but it requires some expertise of the domain of imagination. This study used three-dimensional graphical procedures to describe single sprinkler pattern shapes which would be easily conceivable.

Sprinkler distributions volumes collected in catch cans were utilized to develop these three-dimensional distribution patterns. An access to the computer graphics program "SYMVU" could be made through the Oklahoma State University Computer Center. SYMVU is a computer graphics program written for the purpose of generating three-dimensional displays of data. This program was developed at the Laboratory for Computer Graphics and Spatial Analysis at Harvard University. FORTRAN Subroutine "DATA", available through the Oklahoma State University Computer Center, was used to manipulate the can volumes and to return them to the program in the form that SYMVU would accept. SYMVU then produced the plots that were ready to be plotted by the Oklahoma State University Computer Center Complot Pen Plotter. For better perspectives, an azimuth of 51 degrees and an altitude of 45 degrees were chosen; width and height of the graphs were arbitrarily selected through a preview of the plots on the TEKTRONIX terminal. SYMVU would select its own depth scale based on the highest volume in the data set of any particular test. The highest volume was different for different tests. To establish one single depth scale, for ease of visual comparison between patterns, a fictitious volume of 250 ml was assigned to a corner-can in each test. No corner can received any sprinkler spray during any test and no cans in the field received more than 250 ml of water during the entire test program. This assignment provided a depth scale of 1.00 cm to 1.74 cm. The sprinkler position was located at the intersection of the two diagonals.

With this setup, three-dimensional distribution patterns were obtained for each test repetition. The pertinent test conditions are shown on the patterns; moreover, the speed and the direction of wind are indicated using vectors, 1 cm representing 4 km/hr of wind. Six of these patterns are presented in Figures 14 through 19 and the rest are presented in Appendix F. These plots demonstrated the well-defined donut effects of low pressure at low wind. When the pressure was increased, the donut-shaped patterns approached uniform distributions as long as the wind speed was low. At higher winds, the uniformity of shape was destroyed, yielding to distorted distribution patterns. The pattern distorting characteristics of wind was prevalent throughout irrespective of pressure. These observations were in full agreement with those of Shull and Dylla (1976), and in partial agreement with Seginer and Kostrinsky (1975), who reported that the only effect of wind was in distorting the patterns.

Uniformity of Application, UC

Branscheid and Hart (1968) undertook a study to determine correct methods for utulizing single sprinkler patterns in the prediction of field distribution. They reported that the single sprinkler data when properly

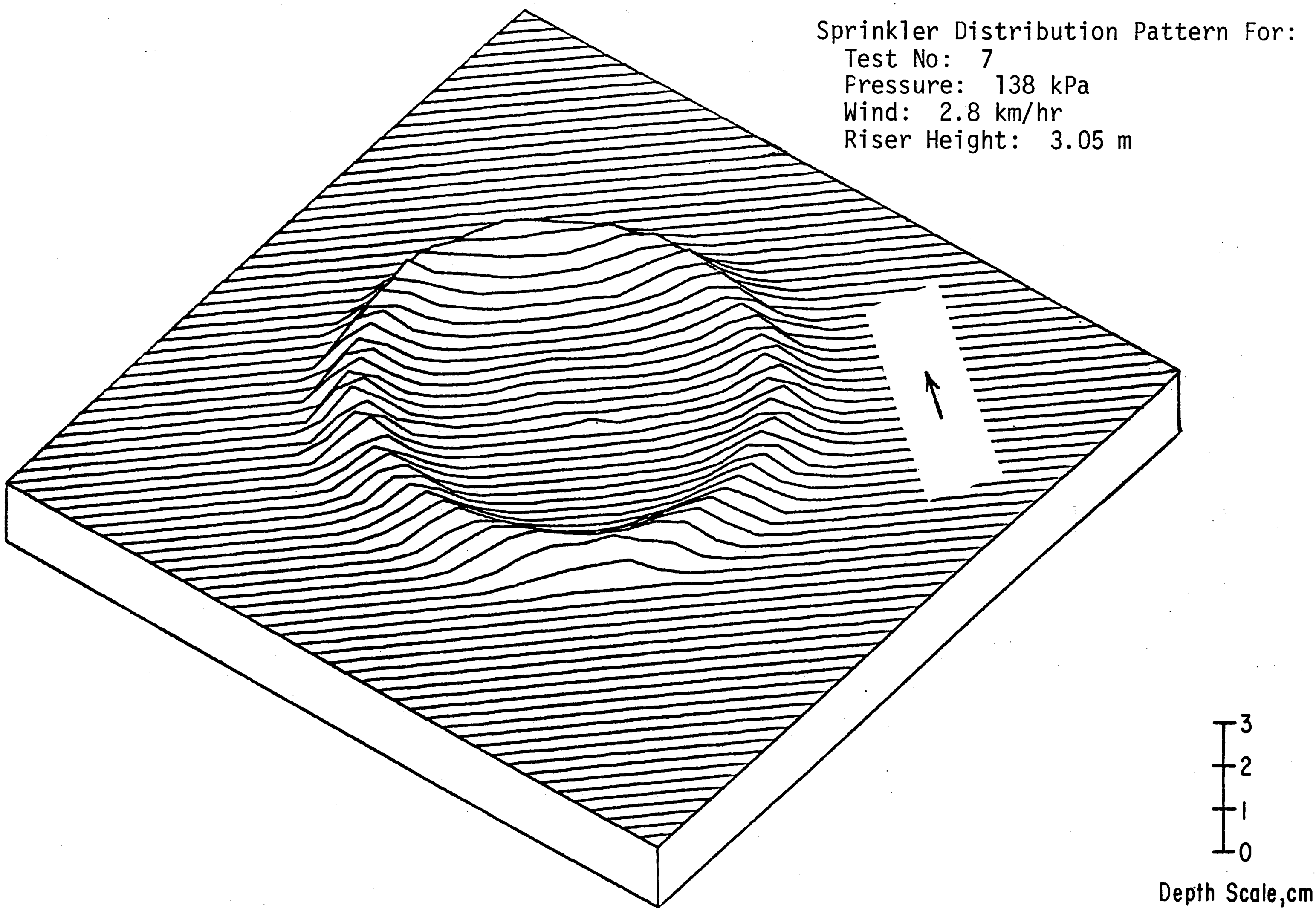

Figure 14. Sprinkler Distribution Pattern Under Low Pressure-Low Wind Conditions

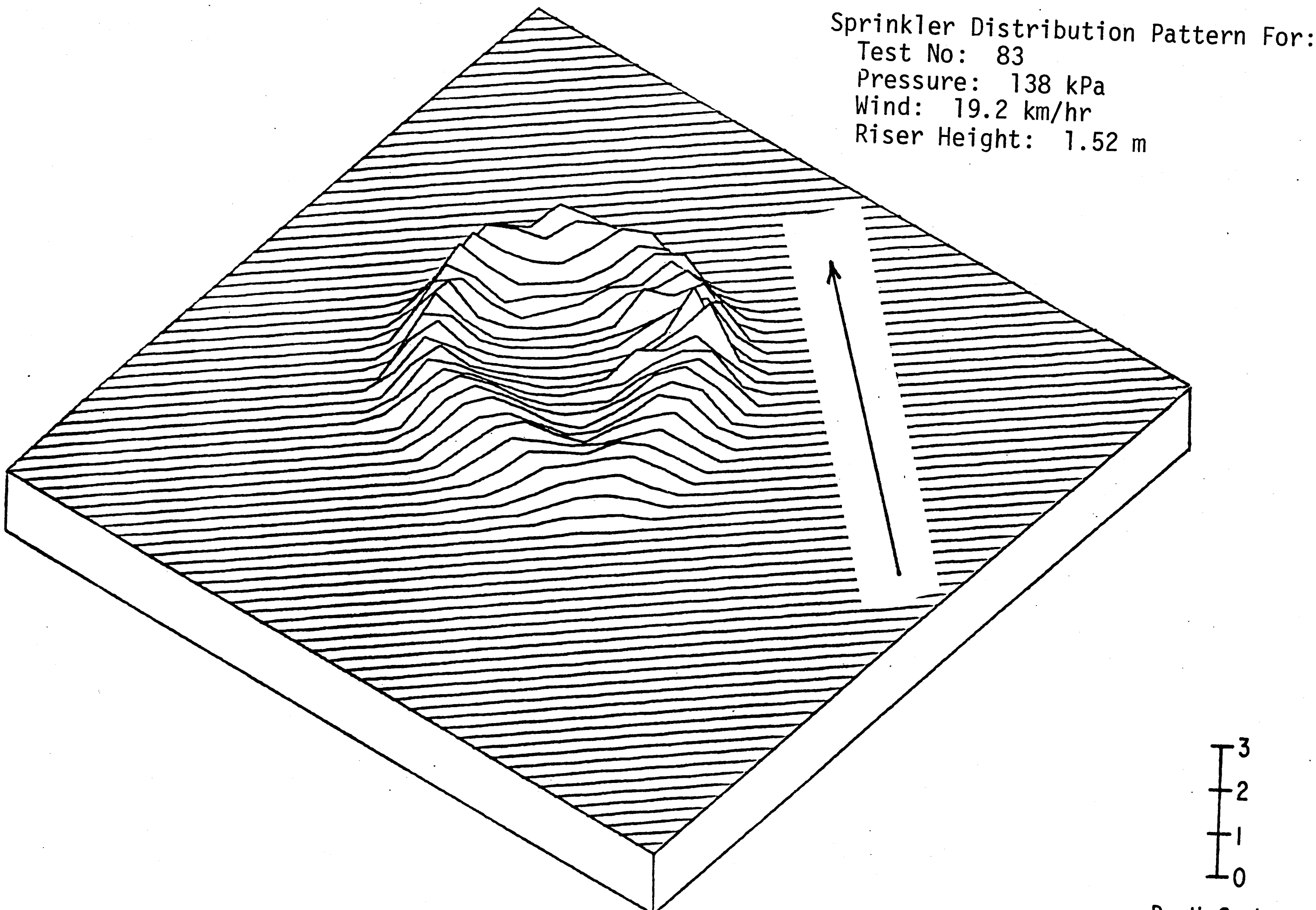

Figure 15. Sprinkler Distribution Pattern Under Low Pressure-High Wind Conditions

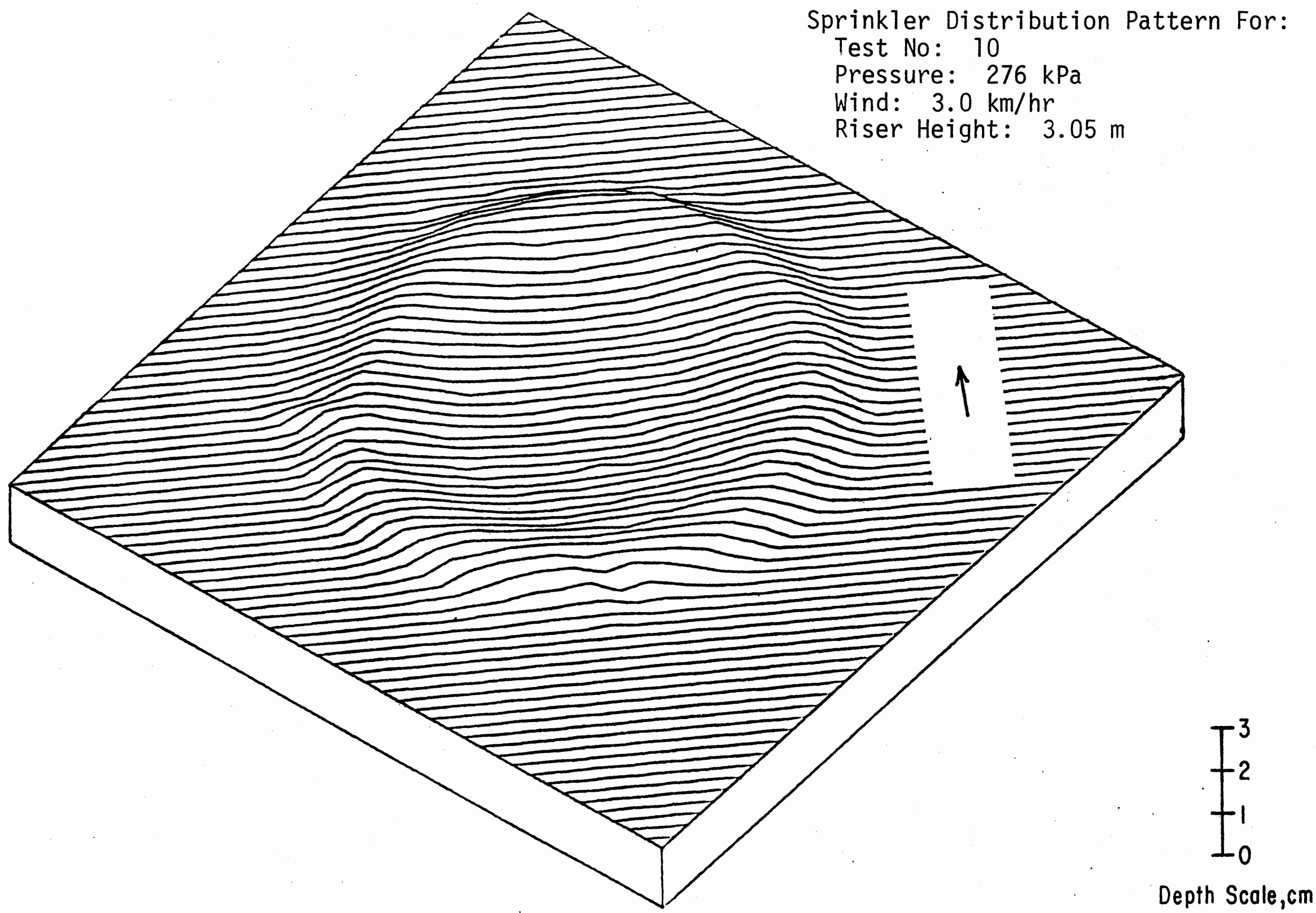

Figure 16. Sprinkler Distribution Pattern Under Medium Pressure-
Low Wind Conditions

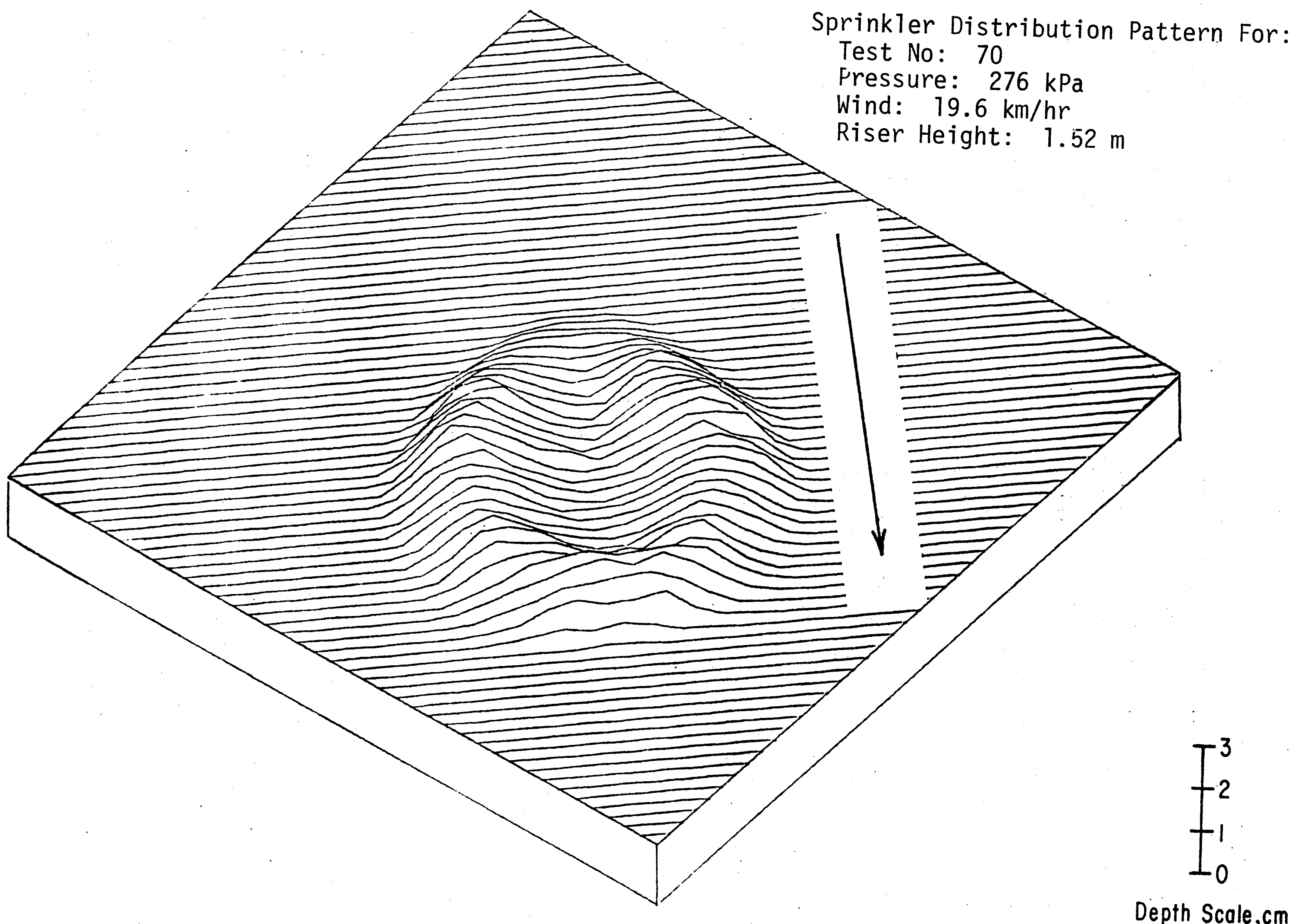

Figure 17. Sprinkler Distribution Pattern Under Medium Pressure-High Wind Conditions

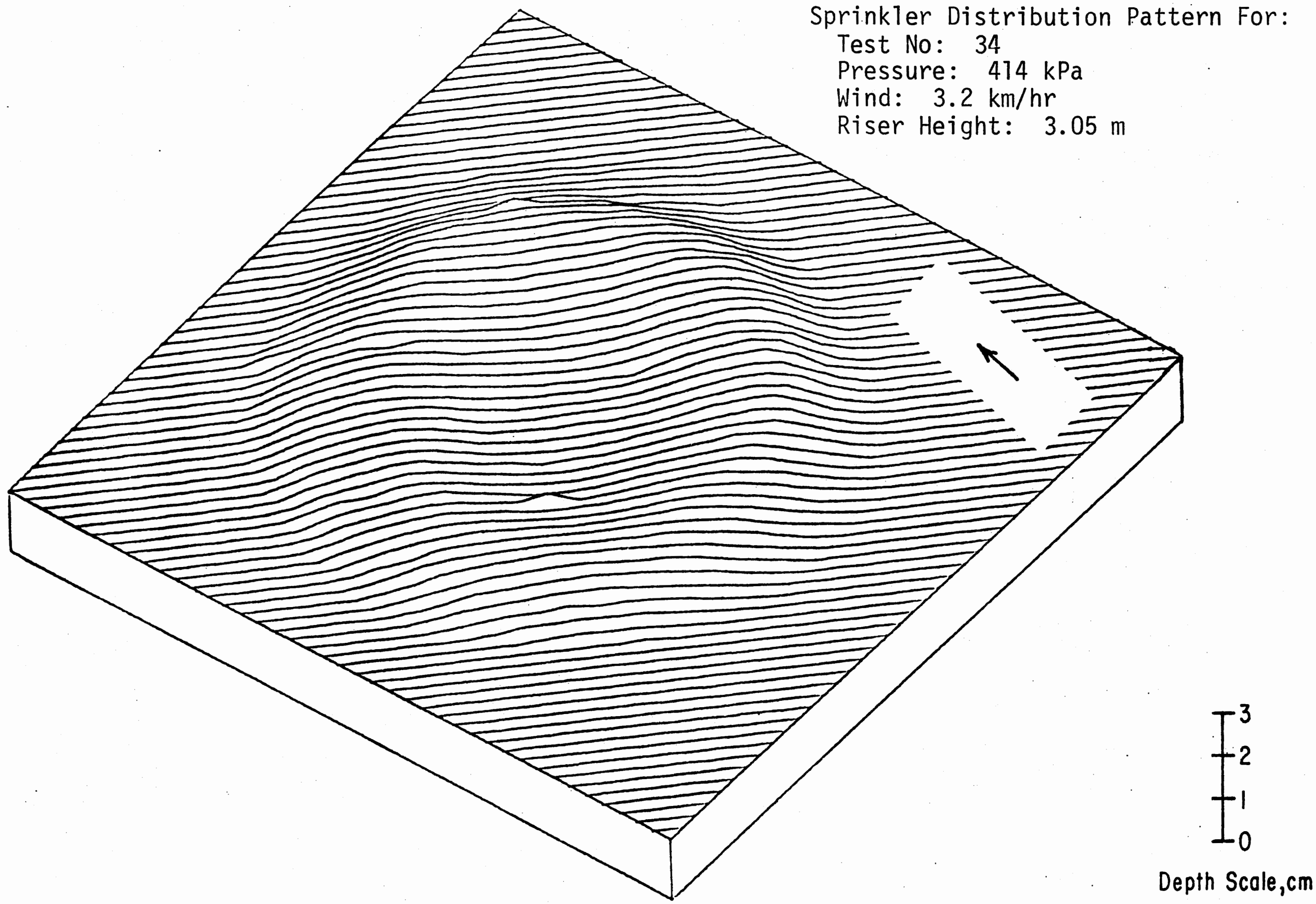

Figure 18. Sprinkler Distribution Pattern Under High Pressure-
Low Wind Conditions

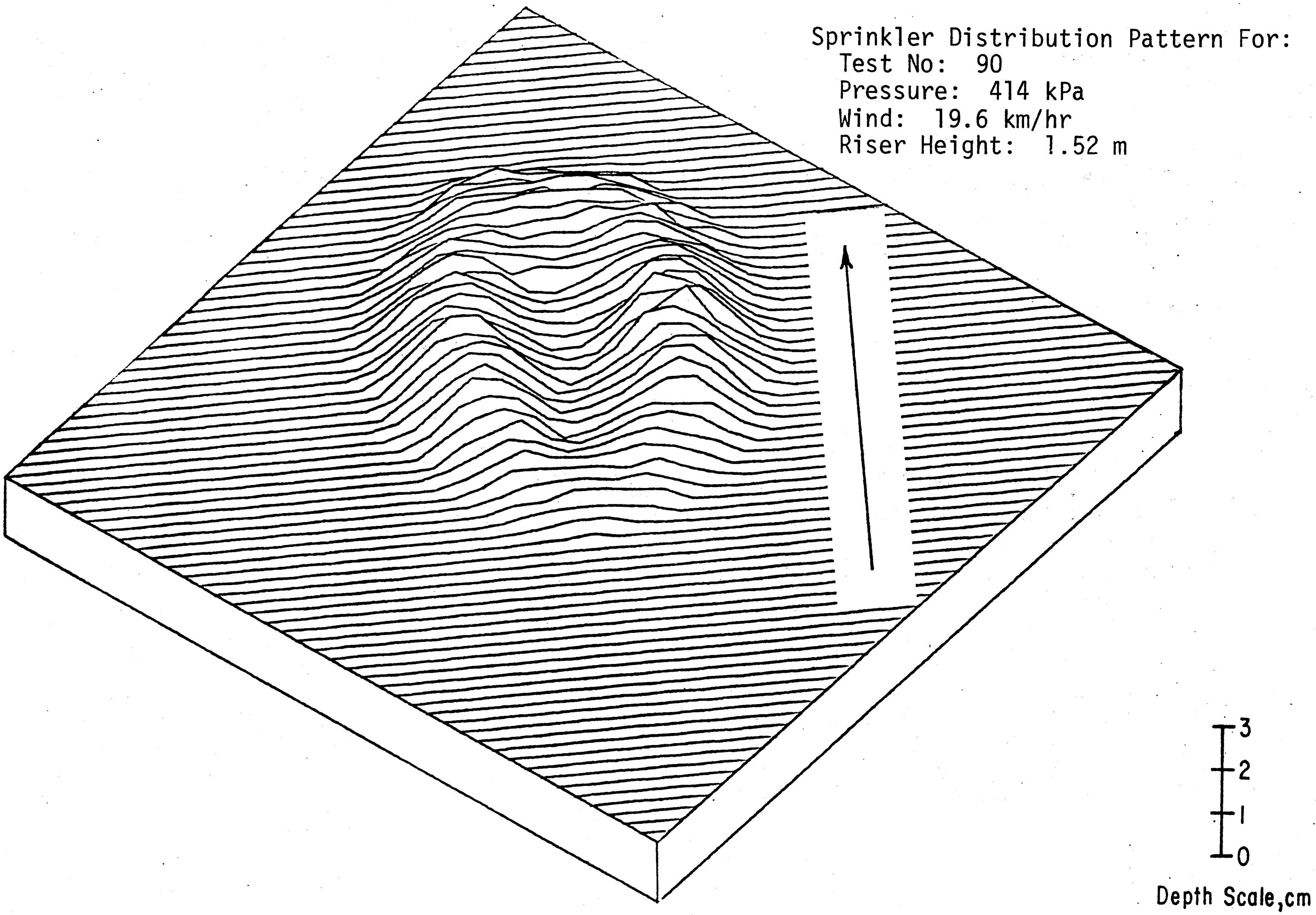

Figure 19. Sprinkler Distribution Pattern Under High Pressure-High Wind Conditions

overlapped predicted field distribution within an error range of 0.15 to 2.35 percent of the actual distribution.

In this study, the uniformity of application was computed in an identical procedure using observation of precipitation depths within an array of the overlapped pattern of many sprinklers. Precipitation depths were assumed to be normally distributed as described by Hart (1961), and Seniwongs et al. (1972). The method used to develop the overlapped pattern was to obtain the distribution from a single stationary sprinkler head, simulate the stationary pattern to a moving one, and then overlap enough of them to obtain the overlapped pattern desired. Simulation and overlapping was performed in the following way: A 41 by 41 array representing the one-meter square grid network was used for every test pattern. The sprinkler riser and the sprinkler head were assigned a position at the center of the array (21, 21 position). The can volume obtained from each stationary test and corrected for suspected errors were placed at the appropriate positions within the array with reference to the position of the sprinkler riser. Depths $D_{c1}(I,J)$ in each can were calculated using Equation (5.6) and the application rate at each can was found using the relationship:

$$A_{r1}(I,J) = \frac{D_{c1}(I,J)}{T_m} \times 60 \qquad (5.21)$$

where $A_{r1}(I,J)$ is the application rate in can (I,J) placed one meter apart (cm/hr). This two-dimensional array of application rates, $A_{r1}(I,J)$, was then simulated to a continuously moving one and a one-dimensional array of simulated and accumulated depths, $D_{a1}(J)$, was generated from it in the following way: An imaginary row of 41 cans, spaced one meter apart, was placed ahead of the continuously moving array, $A_{r1}(I,J)$. A velocity of movement of 16 m/hr (0.015 ft/sec) was assigned to array $A_{r1}(I,J)$, since this is approximately the equivalent speed of rotation of many center-pivot systems. A straight line travel path of $A_{r1}(I,J)$ was assumed as reported by Bittinger and Longenbaugh (1962). Figure 20 represents this simulation of pattern movement.

The depths that would be accumulated in the imaginary row of cans when the pattern $A_{r1}(I,J)$ completely passed over it would be given by:

$$D_{a1}(J) = \frac{S_c}{V_p} \sum_{I=1}^{41} A_{r1}(I,J) \tag{5.22}$$

where

$D_{a1}(J)$ = accumulated depth in can (J) (cm);

S_c = spacing between cans (m); and

V_p = assigned pattern velocity (m/hr).

Since an overall grid size of 41 by 41 was used and this size never failed to catch all the sprinkler spray, an utmost overlapping of 41 sprinklers would be the upper bound. Therefore, 41 arrays of accumulated depths, $D_{a1}(J)$, were placed side by side and meshed toward the center array (21st array) from both sides. Meshing was done by unit increment representing a one-meter move each time to obtain a new array of overlapped depths, $D_{o1}(J)$. $D_{o1}(J)$ would represent the accumulated depths obtained from a complete passage of 41 overlapped patterns; it was generated for each increment of meshing by summing the depths in column J, from the center array. Meshing was continued for 40 increments, each increment representing a spacing between sprinklers. For example, the spacing between sprinklers would be 40 m for the first increment, 39 m for the second increment, and so on until one meter for the 40th increment.

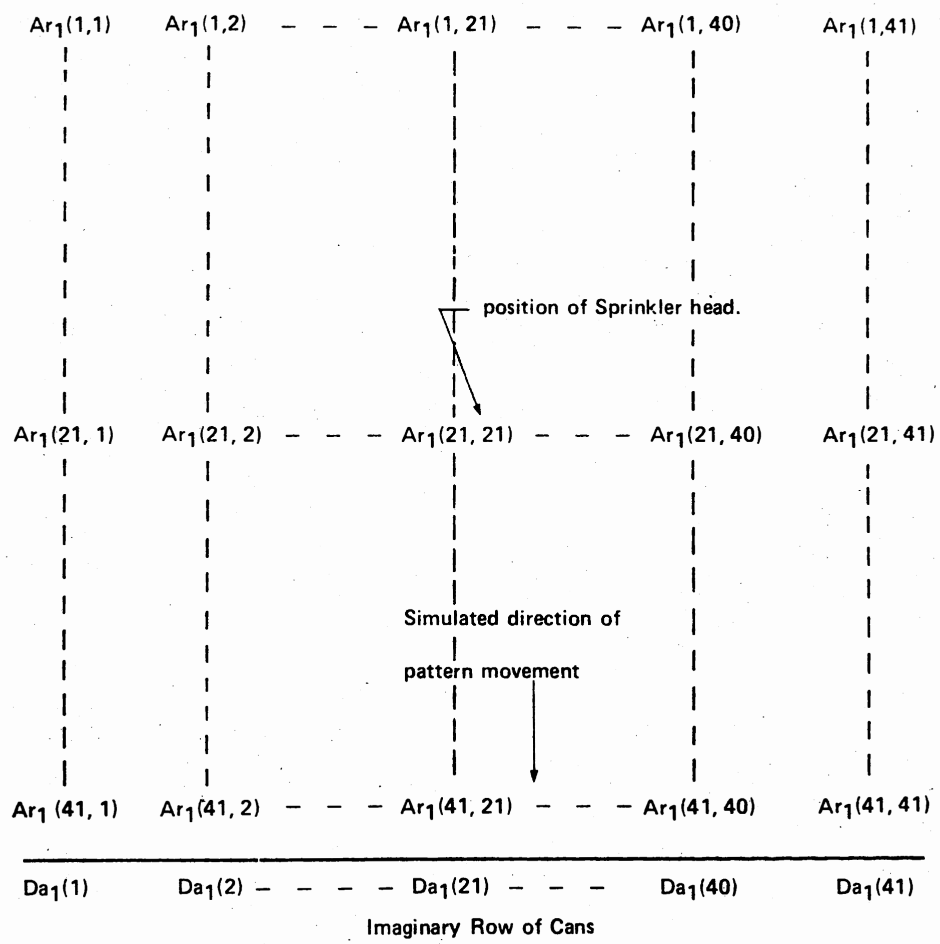

Figure 20. Simulation of Pattern Movement

Real overlapping was always dependent upon the pattern wetted diameter. Array $D_0(J)$ was 41 meters long, having some zero values at both ends representing cans with no water. Positive can depths occurred only within the wetted diameter range. Therefore, during the process of overlapping, it was always possible that the center array (21st array) would have some zero depths in between positive depths. Calculation of uniformities from such $D_{01}(J)$ would be misleading since it did not represent a real overlap. Real overlap occurred first when two wetted diameters of the two adjacent arrays of $D_a(J)$ touched each other. Uniformities were calculated from $D_{01}(J)$ only after real overlaps occurred.

Christiansen's uniformity coefficient was chosen as a measure of uniformity of application. This uniformity equation, given by Equation (2.1) was applied to $D_{01}(J)$ for each increment of meshing to calculate the uniformity resulting from each real overlapping of sprinkler pattern.

Application Rate, AR

The two-dimensional array, $D_{c1}(I,J)$, of the distribution depths caught by each can in the grid network (Equation (5.6)) was utilized to develop a one-dimensional array of simulated application rates, $R_{a1}(J)$.

$R_{a1}(J)$ would represent an array of application rates which would be obtained from a continuously moving single sprinkler pattern. It was generated in the following way.

Accumulated depths already generated at Column J of the array $D_a(J)$ were caught by the time the pattern $A_{r1}(I,J)$ would require to pass completely over the imaginary row of cans placed ahead of it. This time would be given by:

$$T_h(J) = \frac{D_w}{V_p} \times 1000 \qquad (5.23)$$

where $T_h(J)$ is the time required by the moving array $A_{r1}(I,J)$ for a complete passage over the imaginary row of cans (hr), and D_w is the wetted distance between two extreme points in column J (m). $R_{a1}(J)$ was then determined using the equation:

$$R_{a1}(J) = \frac{D_{a1}(J)}{T_h(J)} \qquad (5.24)$$

where $R_{a1}(J)$ are simulated application rates in Column J (cm/hr).

Application rates, $R_{o1}(J)$, for the overlapped patterns were determined meshing 41 identical one-dimensional arrays of application rates, $R_{a1}(J)$, and summing the application rates in Column J of the center overlapped array for each increment in a manner similar to that of meshing the arrays of accumulated depths, $D_{a1}(J)$, and generating the array of overlapped depths $D_{o1}(J)$. The average application rate for each real increment of meshing was computed averaging the 41 values of J from array $R_{o1}(J)$.

This procedure of determining uniformity and average application rate for each sprinkler spacing was utilized for all 72 tests. The uniformity and average application rate for the first real overlapping for each of the 72 tests are shown in Table XII.

Uniformity Model

Results of the uniformities and average application rates were utilized to develop the sprinkler uniformity model. The independent variables that were considered to influence uniformity were spacing between sprinklers (SSP), WS, RHT, PRESS, RH, and T. Uniformity values

TABLE XII

UNIFORMITY RESULTS

Test No (TSL)	Sprinkler Spacing (SSP) (m)	Uniformity (UC) (%)	Application Rate (AR) (cm/hr)
1	22	71	0.20
2	23	65	.20
3	20	78	.15
4	32	49	.17
5	28	63	.17
6	30	67	.13
7	24	74	.17
8	22	73	.18
9	28	64	.15
10	28	77	.15
11	25	57	.16
12	25	77	.21
13	27	69	.17
14	25	57	.19
16	31	60	.16
18	28	65	.17
22	26	81	.26
23	26	71	.24
25	19	85	.25
26	21	83	.29
27	26	52	.22
29	21	82	.28
30	26	71	.25
31	21	75	.26
32	27	67	.24
33	30	58	.21
34	30	55	.16
38	23	76	.19
39	20	71	.15
40	23	62	.19
41	22	86	.24
42	23	68	.16
43	21	69	.15
44	20	75	.19
45	21	82	.24
46	22	72	.16
47	24	60	.19
48	24	66	.15
49	23	65	.20
50	28	50	.18

TABLE XII (Continued)

Test No (TSL)	Sprinkler Spacing (SSP) (m)	Uniformity (UC) (%)	Application Rate (AR) (cm/hr)
51	22	80	.16
52	26	67	.17
53	20	78	.16
54	30	60	.15
55	26	62	.20
56	21	70	.21
57	22	71	.25
58	21	72	.25
59	19	79	.28
60	17	81	.27
61	23	65	.22
62	22	70	.23
63	17	75	.28
64	23	72	.21
65	20	78	.26
66	22	69	.20
67	23	65	.23
68	20	72	.30
69	16	84	.27
70	19	78	.25
71	23	72	.18
72	21	70	.24
73	17	74	.25
74	18	79	.24
75	19	78	.29
76	20	68	.26
83	18	74	.28
88	17	83	.24
89	20	65	.26
90	23	51	.26
91	24	67	.21
92	23	67	.19
93	24	60	.22

corresponding to application rates between 0.76 and 1.78 cm/hr (0.3 and 0.7 in./hr) were utilized since these are the most desirable values from irrigation point of view.

Procedures similar to that of developing and improving the evaporation model were employed. The best three models in original variables were found as the following:

1. UC = 93.76 + 0.012 PRESS (5.25)

(R^2 = 0.19, CV = 2.8 percent, s = 2.76 percent)

2. UC = 98.55 + 0.015 PRESS - 1.24 SSP (5.26)

(R^2 = 0.48, CV = 2.2 percent, s = 2.22 percent)

3. UC = 96.76 + 0.015 PRESS - 1.14 SSP + 0.61 RHT (5.27)

(R^2 = 0.50, CV = 2.2 percent, s = 2.17 percent)

where UC is the uniformity coefficient (percent).

The very low R^2 value demanded attempts to improve the model, if possible. Transformation of variables technique was employed to improve the R^2 value of the uniformity model. The best three models in transformed variables were found as the following:

1. UC = 80.00 + 7.09 Log (PRESS) (5.28)

(R^2 = 0.20, CV = 2.8 percent, s = 2.73 percent)

2. UC = 81.10 + 9.04 Log (PRESS) - 1.26 SSP (5.29)

(R^2 = 0.50, CV = 2.2 percent, s = 2.16 percent)

3. UC = 79.50 + 8.94 Log (PRESS) - 1.16 SSP + 0.61 RHT (5.30)

(R^2 = 0.52, CV = 2.2 percent, s = 2.12 percent)

Plots of the residuals for both the above two types of models, in original variables and in transformed variables, were examined. The best three variable model in original variables (Equation (5.27)) exhibited stronger denials to the regression assumptions as compared to the model in transformed variables. Therefore, this model (Equation (5.27)), although simple, could not be considered superior to the model in transformed variables. The summary of the regression procedures, and the analysis of variance associated with the three variables uniformity model in transformed variables (Equation (5.30)) are shown in Tables XIII and XIV, respectively, while the analysis of variance associated with other models in original variables and in transformed variables (except Equation (5.30)) are presented in Appendices C and D, respectively. The residual plots of Equation (5.30) are presented in Figures 21 through 24. Each of the residual plots exhibited some denials to the regression assumptions. These denials were further reflected by Figure 25, a plot of the model's predicted uniformity versus the observed uniformity values. Although the model predicted uniformities within -8 and +6 percent of the observed values, the plot (Figure 25) exhibited much scatter of the two sets of uniformity values, instead of being clustered along a 45° straight line or fairly close to it. Figure 25 indicated that the model overpredicted uniformities at the lower stream, which means that the model required amendment for better predictions.

Attempts were made to irradicate these anomalies using the weighted least square method of regression as suggested by Draper and Smith (1966). The outcome of the anlaysis did not prove any improvement of the model in terms of its R^2 value and anomalies in the different plots. This suggested that all pertinent independent variables controlling uniformity

TABLE XIII

SUMMARY OF REGRESSION PROCEDURES OF UNIFORMITY MODEL: TRANSFORMED VARIABLES

REGRESSION PROCEDURES FOR DEPENDENT VARIABLE UC

NUMBER IN MODEL	R-SQUARE	VARIABLES IN MODEL	CV, %	s, %	PROB > F
1	0.20	X6	2.8	2.73	.0001
2	0.50	SSP X6	2.2	2.16	.0001
3	0.52	SSP RHT X6	2.2	2.12	.0001
4	0.53	SSP RHT X6 X8	2.2	2.10	.0001
5	0.54	SSP RHT X6 X8 X21	2.2	2.09	.0001
6	0.55	SSP RHT X6 X8 X15 X21	2.1	2.08	.0001
5	0.54	SSP RHT X6 X8 X21	2.2	2.09	.0001

The variables in the above model have all been deemed significant at the 0.1000 significance level

TABLE XIV

ANALYSIS OF VARIANCE OF THE UNIFORMITY MODEL:
TRANSFORMED VARIABLES

STATISTICAL ANALYSIS SYSTEM

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE UC

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F	R-SQUARE	C.V.
REGRESSION	3	1300.95833913	433.65277971	96.39752	0.0001	0.52371713	2.18369%
ERROR	263	1183.12755300	4.49858385			STD DEV	UC MEAN
CORRECTED TOTAL	266	2484.08589214				2.12098653	97.12876

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB>F	PARTIAL SS	F VALUE	PROB>F
X6	1	509.03608967	113.15474	0.0001	767.08023246	170.51594	0.0001
SSP	1	738.78025549	164.22507	0.0001	568.70871606	126.41839	0.0001
RHT	1	53.14199398	11.81305	0.0007	53.14199398	11.81305	0.0007

SOURCE	B VALUES	T FOR H0:B=0	PROB>|T|	STD ERR B	STD B VALUES
INTERCEPT	79.50002575	47.21502	0.0001	1.68378693	0.0
X6	8.93982686	13.05818	0.0001	0.68461533	0.57043192
SSP	-1.15984819	-11.24359	0.0001	0.10315636	-0.51328681
RHT	0.61174111	3.43701	0.0007	0.17798633	0.15303791

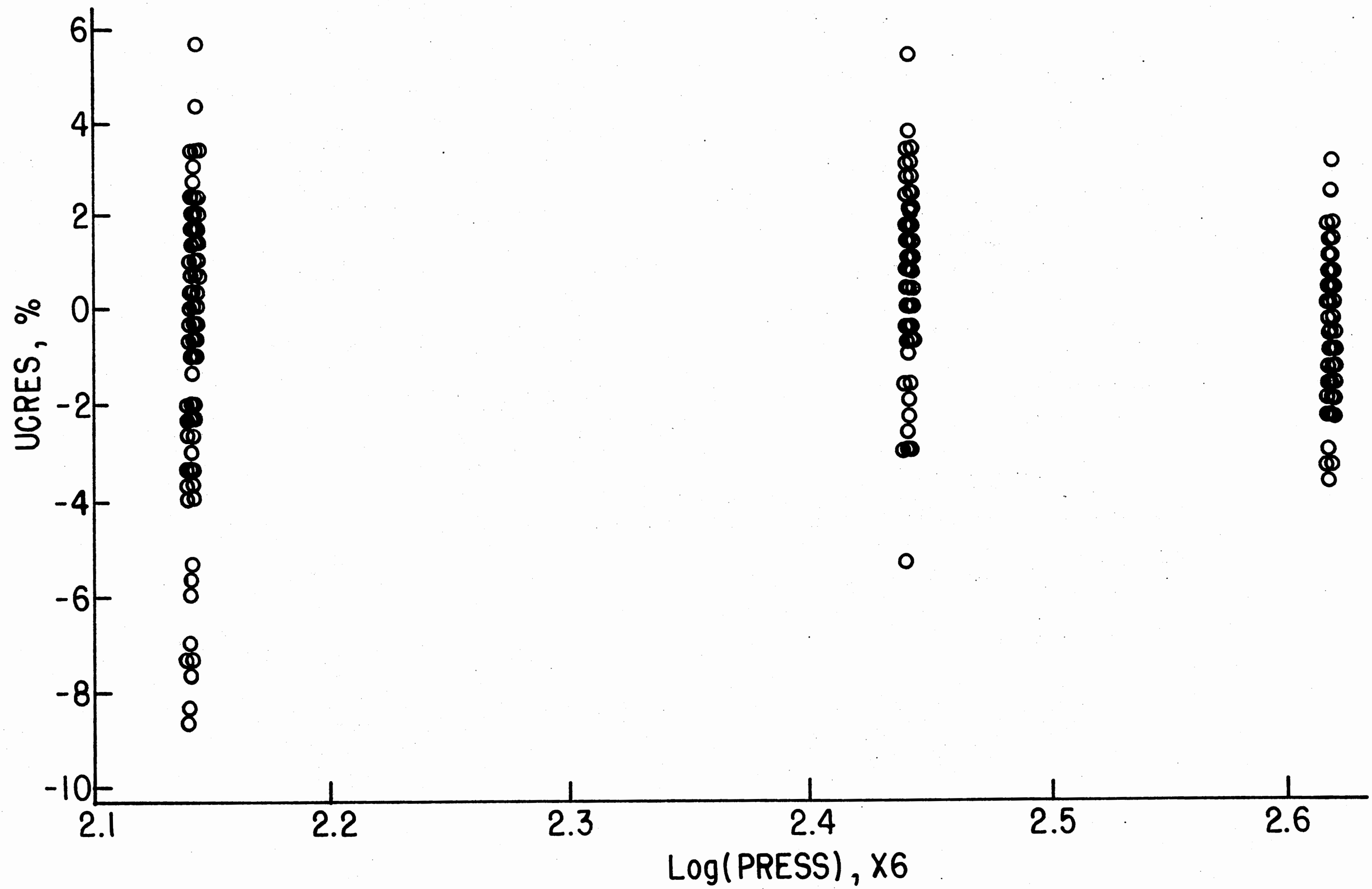

Figure 21. Plot of Residual, UCRES Versus Log (Pressure), X6

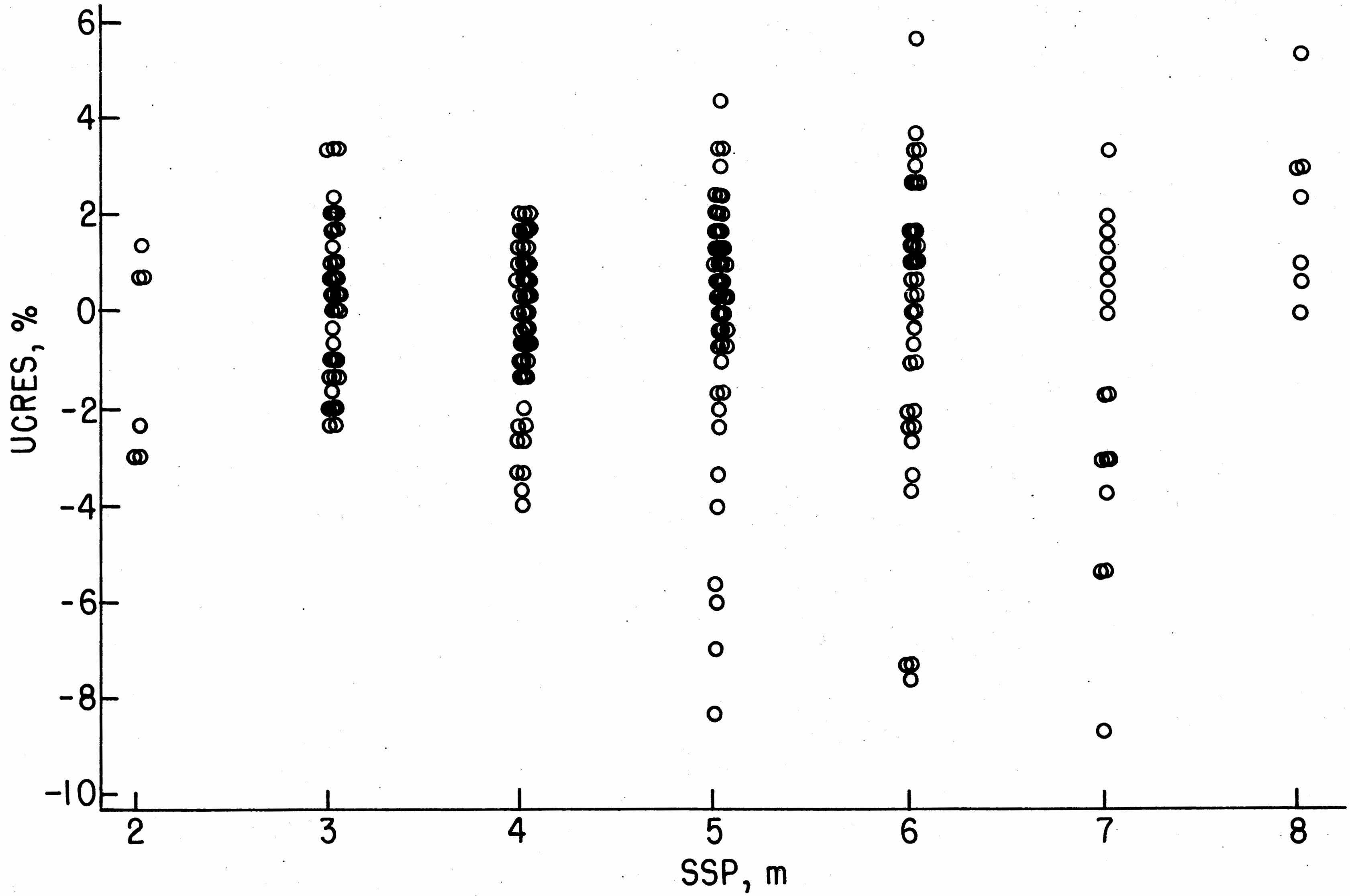

Figure 22. Plot of Residual, UCRES Versus Sprinkler Spacing, SSP

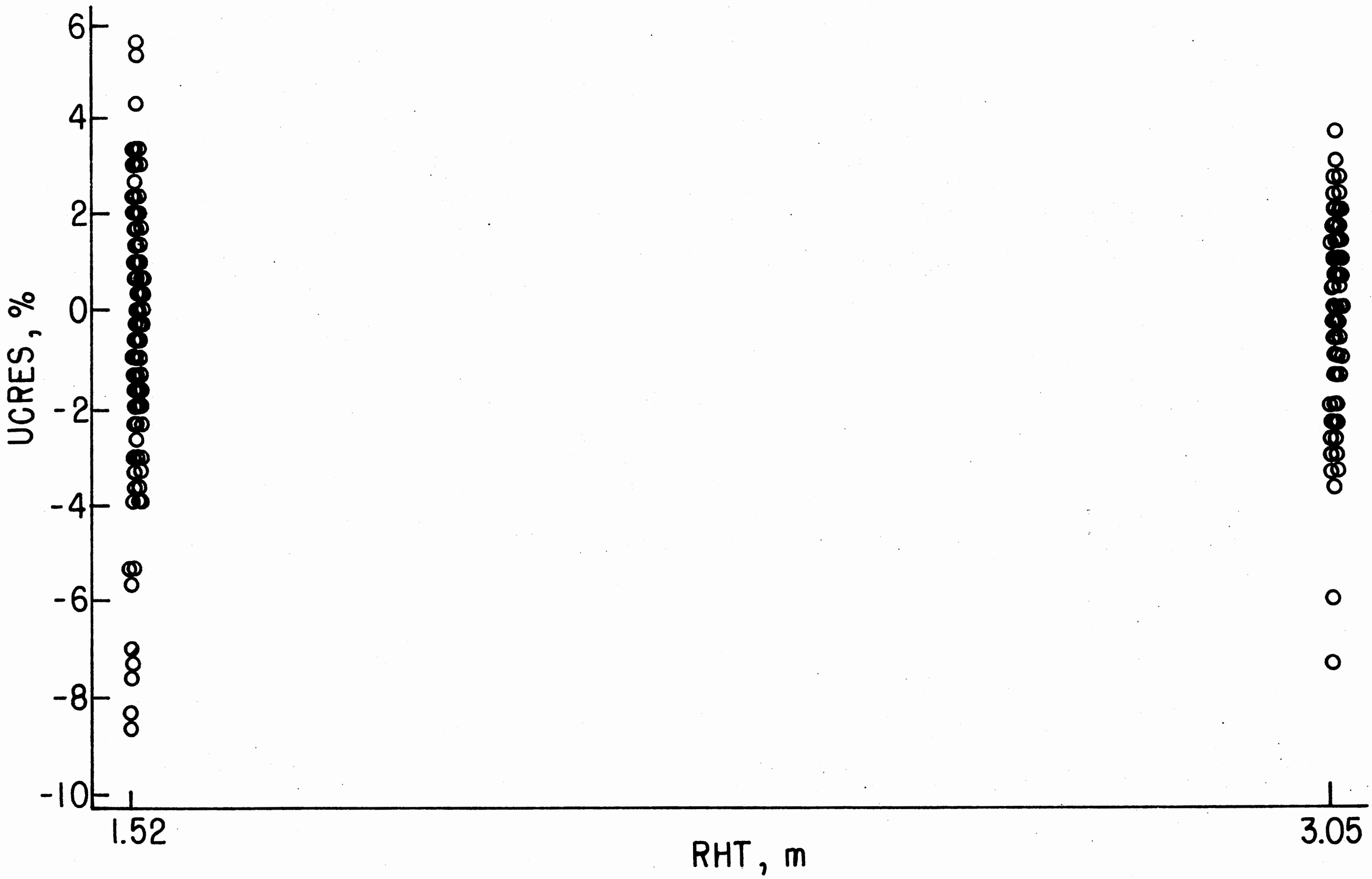

Figure 23. Plot of Residual, UCRES Versus Riser Height, RHT

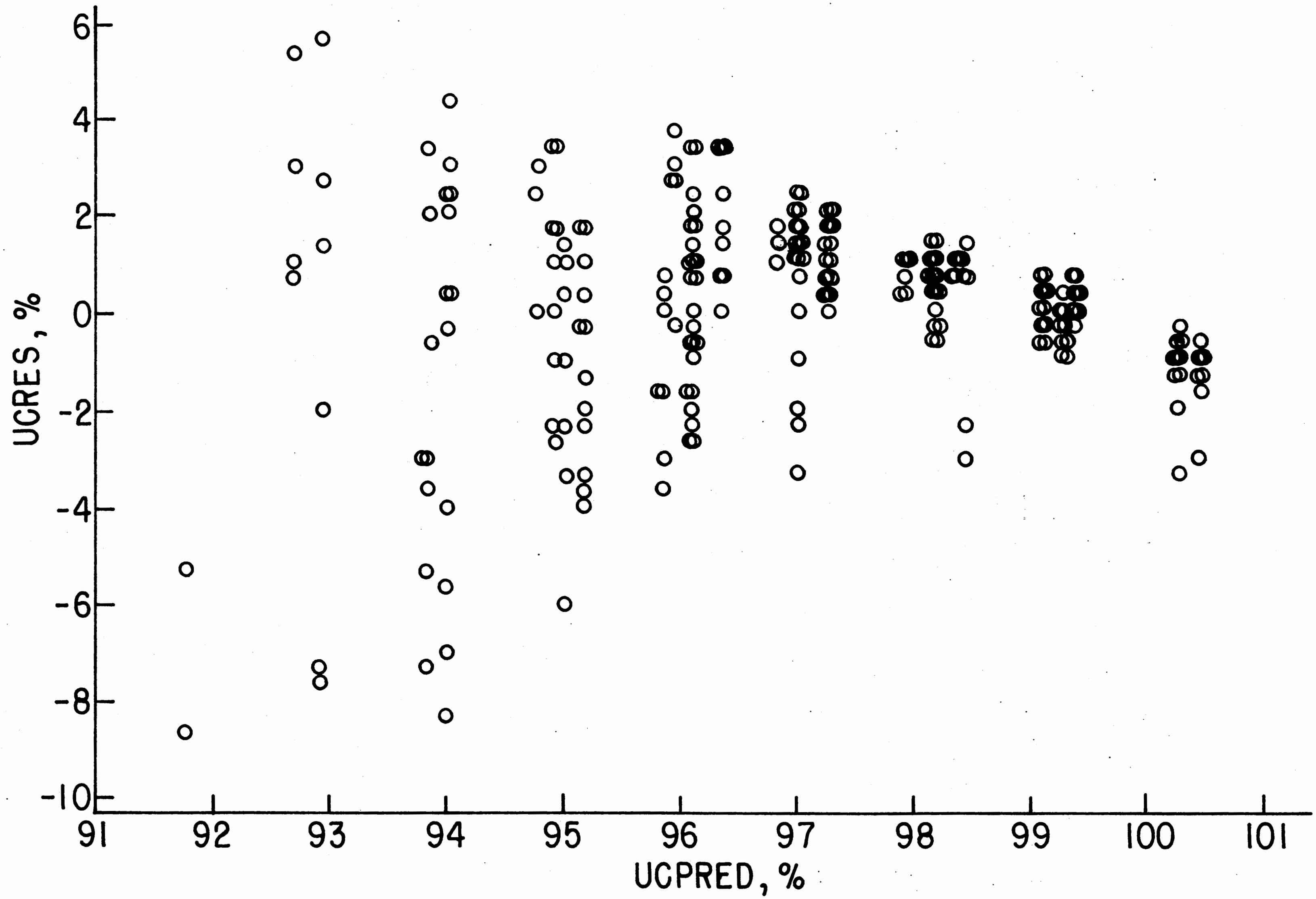

Figure 24. Plot of Residual, UCRES Versus Predicted Uniformity, UCPRED

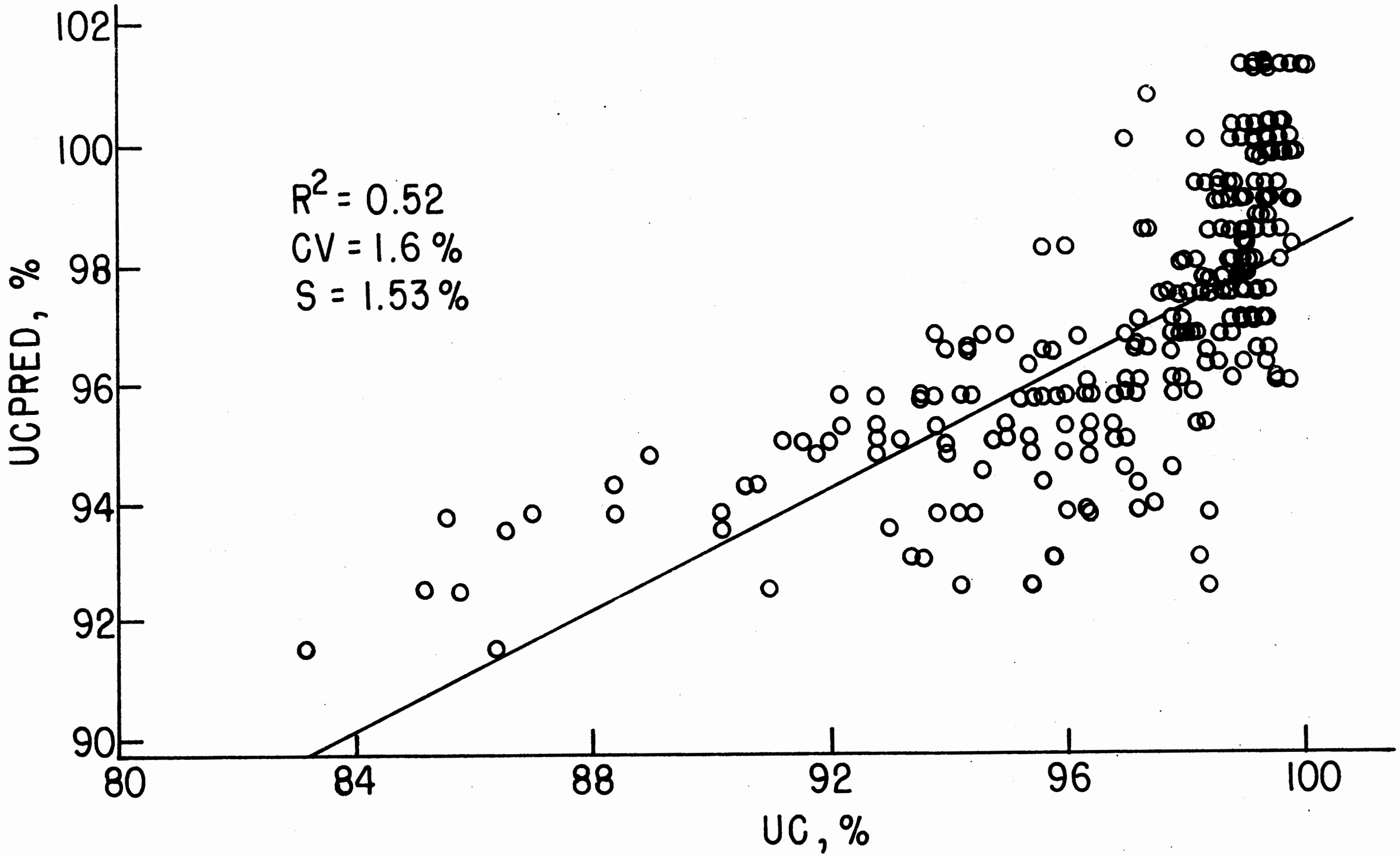

Figure 25. Plot of Predicted Uniformity, UCPRED Versus Observed Uniformity, UC

were probably not considered in the model. Speed and uniformity of sprinkler rotation, as indicated by Christiansen (1941) could have been considered as another independent variable. It is suspected that if this variable is included in the independent variables list, the model might show a better performance from a statistical point of view and consequently it might predict uniformities more accurately.

Therefore, it was concluded that with the available data, a better model other than the one established in transformed variables (Equation (5.30)) was not possible. Thus, the three variable model in transformed variables given below was chosen as the uniformity model to give a fairly good but not the best estimate of sprinkler uniformity.

$$UC = 79.50 + 8.94 \text{ Log (PRESS)} - 1.16 \text{ SSP} + 0.61 \text{ RHT} \qquad (5.30)$$

It was observed from the established uniformity model (Equation (5.30)) that the uniformity increased with increase in PRESS and RHT and with decrease in SSP. It was also indicated in Table XIII that PRESS, SSP, and RHT were the independent variables in order of decreasing importance to influence uniformity; PRESS was shown to have the greatest influence on uniformity and RHT the least.

Optimum Can Spacing Criterion

Data collected from the group-A tests were utilized to determine an optimum can spacing criterion for the catch can method of sprinkler testing. In all the group-A tests, volumes of water distributed by the single stationary sprinkler were collected in cans, spaced one meter apart. These can volumes, described as $V_{C1}(I,J)$, were converted to distribution depths using the following relationship as described earlier.

$$D_{c1}(I,J) = \frac{V_{c1}(I,J)}{A_c} \qquad (5.6)$$

$D_{c1}(I,J)$ represented the depths in cans in the 41 by 41 grid network with a can spacing of one meter for a particular test. Values of $D_{c1}(I,J)$ were utilized to develop many arrays which represent two-dimensional depth arrays (distribution patterns) with different can spacings. The generation of these depth arrays were performed in the following way.

With respect to the sprinkler position (center of the grid system) each alternate cans of $D_{c1}(I,J)$ were removed to given an array $D_{c2}(I,J)$, representing a new depth array where the cans would be two meters apart; when every third can was removed from $D_{c1}(I,J)$, $D_{c3}(I,J)$ would result, representing another new depth array with a three-meter can spacing. This procedure of generating successively new depth arrays from one original array, $D_{c1}(I,J)$ was continued for each test until a cutoff point was encountered. Percent of wetted area represented by each can (PCTA) was used as a criterion of cutoff point in the generation of the depth arrays. PCTA was computed by:

$$PCTA = \frac{4}{\pi}\left(\frac{S_c}{D_p}\right)^2 100 \qquad (5.31)$$

where S_c is the spacing between cans (m), and D_p is the wetted diameter of distribution pattern (m). Based on the work of Davis (1966), it was assumed that when PCTA of a depth array would equal or exceed 10 percent, the uniformities computed from it would be erroneous and misleading. This conditioning of PCTA resulted in seven to ten arrays of depth with different can spacings for all the group-A tests.

Following procedures discussed earlier in this chapter, each of the arrays of $D_{c1}(I,J)$, $D_{c2}(I,J)$, etc. were simulated to continuously moving arrays to result in simulated and accumulated depth arrays of $D_{a1}(I,J)$, $D_{a2}(I,J)$, etc. Uniformities were computed using Christiansen's uniformity equation (Equation 2.1) from $D_{a1}(I,J)$ for one meter can spacing, $D_{a2}(I,J)$ for two meter can spacing, and so on.

To determine the effect of increasing PCTA on uniformity, which would be equivalent to studying the effect of increasing can spacing on uniformity, the group-A tests had to be separated in six sub-groups depending upon the test conditions. It was observed from the uniformity model (Equation (5.30)) that PRESS and RHT were the important variables influencing UC. Therefore, the following sub-groups were made to eliminate the effect of the above two variables on UC within each sub-group:

1. Low Pressure-Low Riser Tests (LPLR)
2. Medium Pressure-Low Riser Tests (MPLR)
3. High Pressure-Low Riser Tests (HPLR)
4. Low Pressure-High Riser Tests (LPHR)
5. Medium Pressure-High Riser Tests (MPHR)
6. High Pressure-High Riser Tests (HPHR).

This kind of grouping would allow one to compare PCTA against UC within each sub-group and thereby to determine its effect on UC. Since each sub-group did have multiple values of PCTA and UC for the same spacing (because several PCTA and UC values corresponding to the same can spacing were brought together from different tests), they had to be averaged for each can spacing to give mean PCTA (MNPCTA) and mean UC (MNUC) before a comparison could be made. The results of the six sub-groups are shown in Tables XV through XX. Based on these results, the comparison was demonstrated graphically by Figure 26, which is a combination of six plots of

TABLE XV

UNIFORMITY RESULTS OF
SUB-GROUP LPLR

SPRINKLER SPACING (m)	MNPCTA (%)	MNUC (%)
1	0.33	71.8
2	1.32	72.2
3	3.02	71.3
4	5.36	70.0
5	7.94	73.5
6	12.58	66.8
7	11.11	58.6

TABLE XVI

UNIFORMITY RESULTS OF
SUB-GROUP MPLR

SPRINKLER SPACING (m)	MNPCTA (%)	MNUC (%)
1	0.23	69.0
2	0.91	69.0
3	2.06	68.4
4	3.61	73.0
5	5.93	73.8
6	7.67	68.4
7	12.59	63.8
8	11.91	76.2

TABLE XVII

UNIFORMITY RESULTS OF
SUB-GROUP HPLR

SPRINKLER SPACING (m)	MNPCTA (%)	MNUC (%)
1	0.20	61.9
2	0.80	62.1
3	1.77	63.2
4	3.18	59.9
5	4.75	67.2
6	6.95	62.1
7	9.64	67.7
8	11.58	71.6
9	11.81	83.4

TABLE XVIII

UNIFORMITY RESULTS OF
SUB-GROUP LPHR

SPRINKLER SPACING (m)	MNPCTA (%)	MNUC (%)
1	0.24	71.8
2	0.95	71.2
3	2.14	71.7
4	3.90	70.1
5	6.02	63.8
6	8.70	68.3
7	11.83	69.6
8	12.50	83.5

TABLE XIX

UNIFORMITY RESULTS OF
SUB-GROUP MPHR

SPRINKLER SPACING (m)	MNPCTA (%)	MNUC (%)
1	0.18	69.3
2	0.74	69.5
3	1.64	70.0
4	2.90	71.2
5	4.70	67.5
6	6.38	65.9
7	8.94	67.4
8	11.76	75.3
9	11.57	82.7

TABLE XX

UNIFORMITY RESULTS OF
SUB-GROUP HPHR

SPRINKLER SPACING (m)	MNPCTA (%)	MNUC (%)
1	0.17	60.8
2	0.66	61.0
3	1.50	61.6
4	2.73	61.3
5	4.12	59.0
6	6.20	62.4
7	8.13	67.9
8	10.58	67.9
9	12.38	70.4

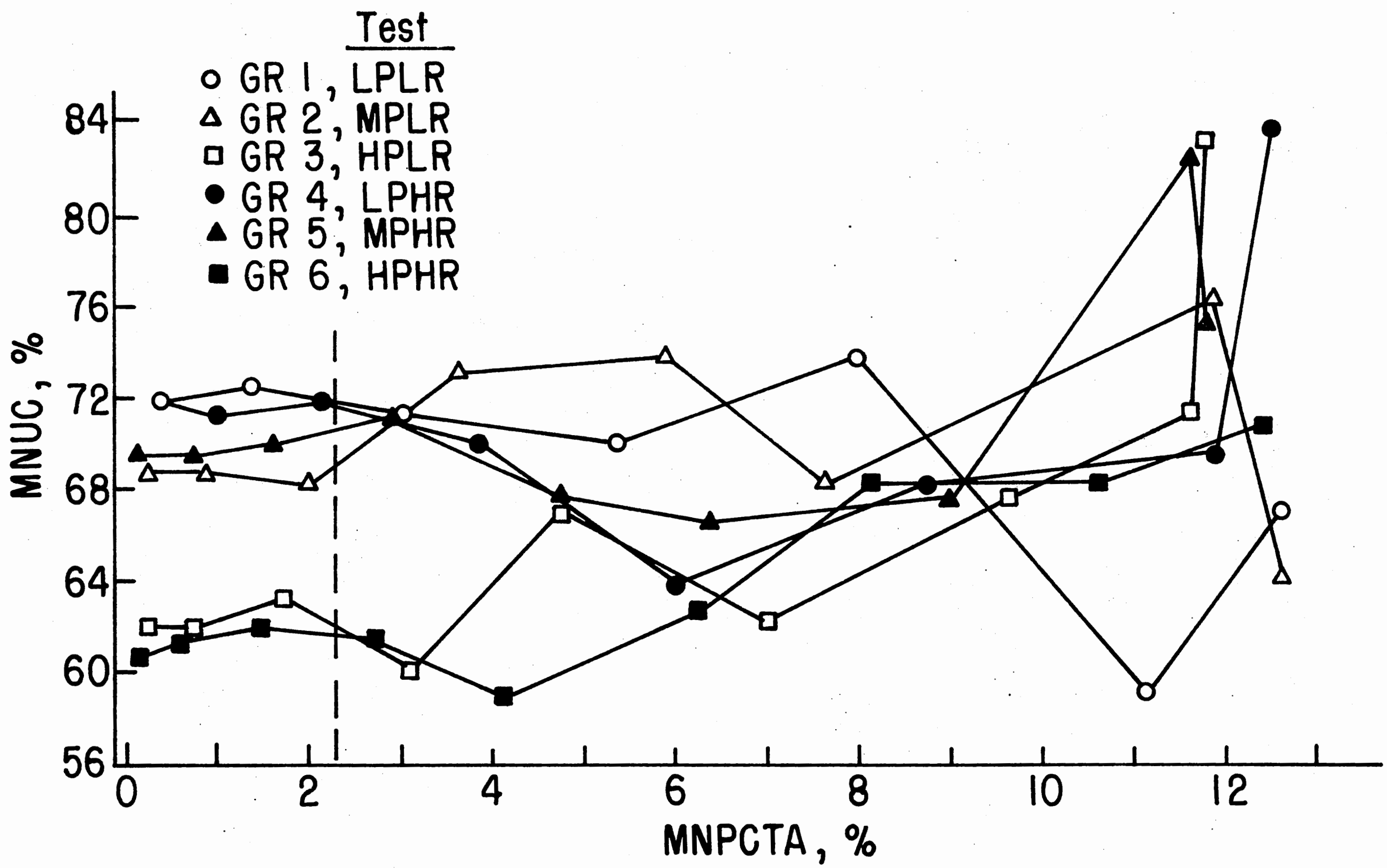

Figure 26. Combined Plots of Mean Uniformity, MNUC Versus Mean Percent of Sampling Area, MNPCTA for the Six Sub-groups

MNUC versus MNPCTA for all six sub-groups. The plots demonstrated that up to a certain value of PCTA, UC is independent of PCTA; UC values had erratic fluctuations beyond this value, implying that above this optimal PCTA value UC becomes highly unreliable. Therefore, this optimal value of PCTA, which was found as 2.25, was considered as the maximum allowable PCTA value to identify uniformities within ±1.3 percent of the actual values. Of course, this optimal PCTA of 2.25 percent is not a very rigid one and it could be extended even up to 9.0 percent, in which case the uniformity obtained would be within ±9.0 percent instead of ±1.3 percent of the observed values. The PCTA values were determined using the plots of Figure 26 and are presented in Table XXI.

Use of Evaporation Suppressant

Data from group-B tests were utilized to determine the effect of using suppressant in the catch cans on evaporation. Four ml of kerosene was used in each can as evaporation suppressant in this study. Before each test, 50 percent of the cans were charged with kerosene as described in Chapter IV. Can volumes from each test were grouped in pairs--group I and group II. Group I data were related to the volumes of "water only" in the cans and group II to the volumes of "water plus kerosene" only.

Evaporation loss from group I cans was determined employing procedures described earlier in this chapter, and using Equation (5.8) on the can volumes (water only).

Evaporation loss from group II cans could not be determined directly using the can volumes, since the can volumes contained both water and kerosene volumes. Volumes of water in group II cans were separated by the following procedure.

TABLE XXI

MEAN UNIFORMITIES IN THE SIX SUB-GROUPS

PCTA (%)	PERCENT VARIATIONS IN UC IN SUB-GROUPS						MAXIMUM VARIATION (%)
	LPLR	MPLR	HPLR	LPHR	MPHR	HPHR	
2.25	0.67	0.80	0.95	1.00	1.30	0.80	1.30
9.00	4.20	5.30	6.80	7.80	5.00	9.00	9.00

During each test, 10 cans were placed in the field with a 4 ml pre-measured amount of kerosene in each. At the end of the test, these cans were recorded. The average loss in ml determined from these 10 can readings were considered as the loss of kerosene during the test. Volumes of kerosene remaining in the cans in the grid network were determined by subtracting the average loss of kerosene from the initial volume of 4 ml of kerosene added to the cans. The volumes of water plus kerosene were then reduced by the amount of kerosene remaining in the cans at the end of the test to give the volumes of water only in the grid cans.

Procedures for determining loss along with Equation (5.8) could then be utilized to compute evaporation loss from group II cans.

Evaporation losses were computed for all group-B tests and the results are shown in Table XXII. The table shows a marked difference in evaporation between group I and group II, with group I always showing higher losses. To examine this, a paired t-test was performed on the two sets of evaporation losses--evaporation from water only and evaporation from water charged with kerosene. The t-test computed a probability value of 0.0001 on the hypothesis that the difference between the two evaporation losses were zero,or equivalently that there was no difference between group I and group II evaporation losses. The highly significant t-value suggested that evaporation was significantly lower for group II cans than for group I cans. This indicated that use of suppressant is of significant value in retarding evaporation from catch cans.

This conclusion was based on nine tests of 138, 276, and 414 kPa of pressures, each repeated three times; and of RH, WS, and T ranges between 26 and 54 percent, 6 and 17 km/hr, and 9 and 31°C, respectively.

TABLE XXII

EVAPORATION RESULTS OF GROUP-B TESTS: COMPARISON OF EVAPORATION USING (a) NO SUPPRESSANT (EVAP), AND (b) KEROSENE AS SUPPRESSANT (EVAKERO)

TEST NO	PRESS (kPa)	REP (#)	WS (km/hr)	RH (%)	T (°C)	EVAP (%)	EVAKERO (%)	EVAP-EVAKERO
79	138	1	11.2	27	31	35.7	23.3	12.40
81	138	2	16.0	39	14	30.2	14.1	16.11
85	138	3	9.8	37	20	20.4	7.4	13.00
78	276	1	10.0	33	28	32.4	24.9	7.52
80	276	2	17.4	54	9	21.8	16.4	5.39
86	276	3	5.8	40	22	26.3	17.3	9.07
77	414	1	5.9	27	28	36.6	26.7	9.85
82	414	2	12.7	33	16	37.1	23.6	13.45
87	414	3	7.8	26	27	34.4	22.6	11.85

Therefore, it calls for further investigation with more test results and a wider range of variable values.

Relationship Between Sprinkler Evaporation Loss and Pan Evaporation Loss

Attempts were made to develop an empirical relationship between sprinkler evaporation loss and pan evaporation loss. Evaporation loss determined from group-A tests (EVAP) and pan evaporation records kept during each of the above group-A tests and converted to pan evaporation loss (PANEVA) are shown in Tables III through VI. These two losses were utilized to develop the relationship.

Procedures similar to those of developing the evaporation model were employed. It was observed that sprinkler evaporation loss (EVAP) was best described by the pan evaporation (PANEVA) data when the pan evaporation loss was transformed to logarithmic and square root functions. The analysis resulted in the following model:

$$\text{EVAP} = 37.14 + 11.27 \text{ Log (PANEVA)} + 54.04 \text{ (PANEVA)}^{\frac{1}{2}} \qquad (5.32)$$

$$(R^2 = 0.68, \text{ CV} = 29 \text{ percent, s} = 8.07 \text{ percent})$$

where PANEVA is the evaporation from the pan (cm/hr).

The analysis of variance associated with this model is shown in Table XXIII and different plots of this model are shown in Figures 27 through 29. The highly significant F value indicated the adequacy of the model and the residual plots practically displayed no violations to the regression assumptions. Therefore, this model would be useful in estimating evaporation loss from pan evaporation records in localities with known weather conditions. Little tendencies of violations to regression

TABLE XXIII

ANALYSIS OF VARIANCE OF EVAPORATION MODEL:
LOG (PAN EVAPORATION), X2, AND
(PAN EVAPORATION)$^{1/2}$, X4 AS
INDEPENDENT VARIABLES

STATISTICAL ANALYSIS SYSTEM
ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE EVAP

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F	R-SQUARE	C.V.
REGRESSION	2	9556.14807417	4778.07403708	73.31327	0.0001	0.68001712	29.13685%
ERROR	69	4496.65701333	65.16894222			STD DEV	EVAP MEAN
CORRECTED TOTAL	71	14052.80508750				8.07272830	27.70625

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB>F	PARTIAL SS	F VALUE	PROB>F
X2	1	9428.54484626	144.67850	0.0001	310.88026163	4.77037	0.0324
X4	1	127.60322791	1.95804	0.1662	127.60322791	1.95804	0.1662

SOURCE	B VALUES	T FOR H0:B=0	PROB>|T|	STD ERR B	STD B VALUES
INTERCEPT	37.13585456	2.42469	0.0179	15.31573224	0.0
X2	11.27423562	2.18412	0.0324	5.16191523	0.50794580
X4	54.03971046	1.39930	0.1662	38.61913295	0.32542554

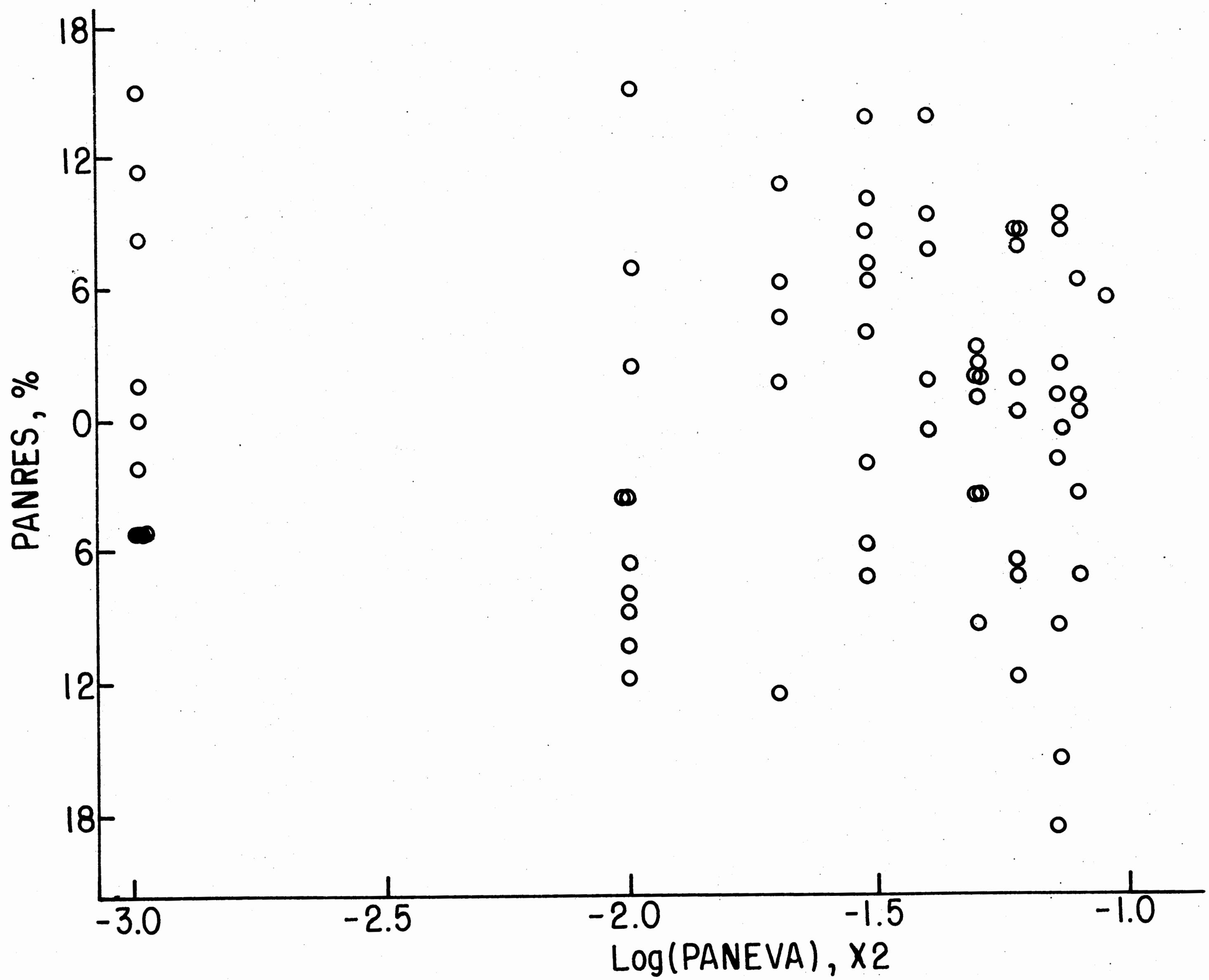

Figure 27. Plot of Residual, PANRES Versus Log (Pan Evaporation), X2

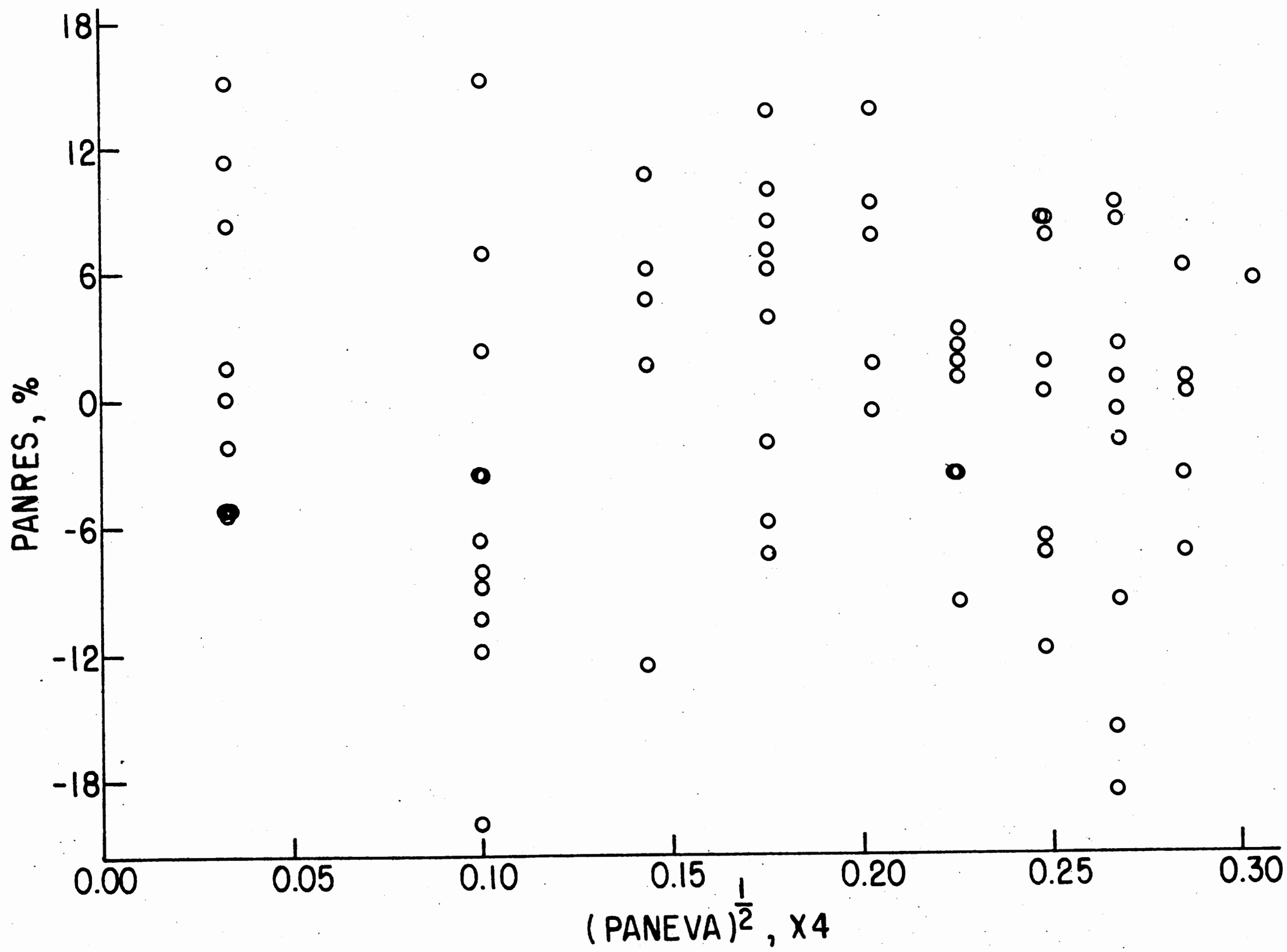

Figure 28. Plot of Residual, PANRES Versus (Pan Evaporation)$^{\frac{1}{2}}$, X4

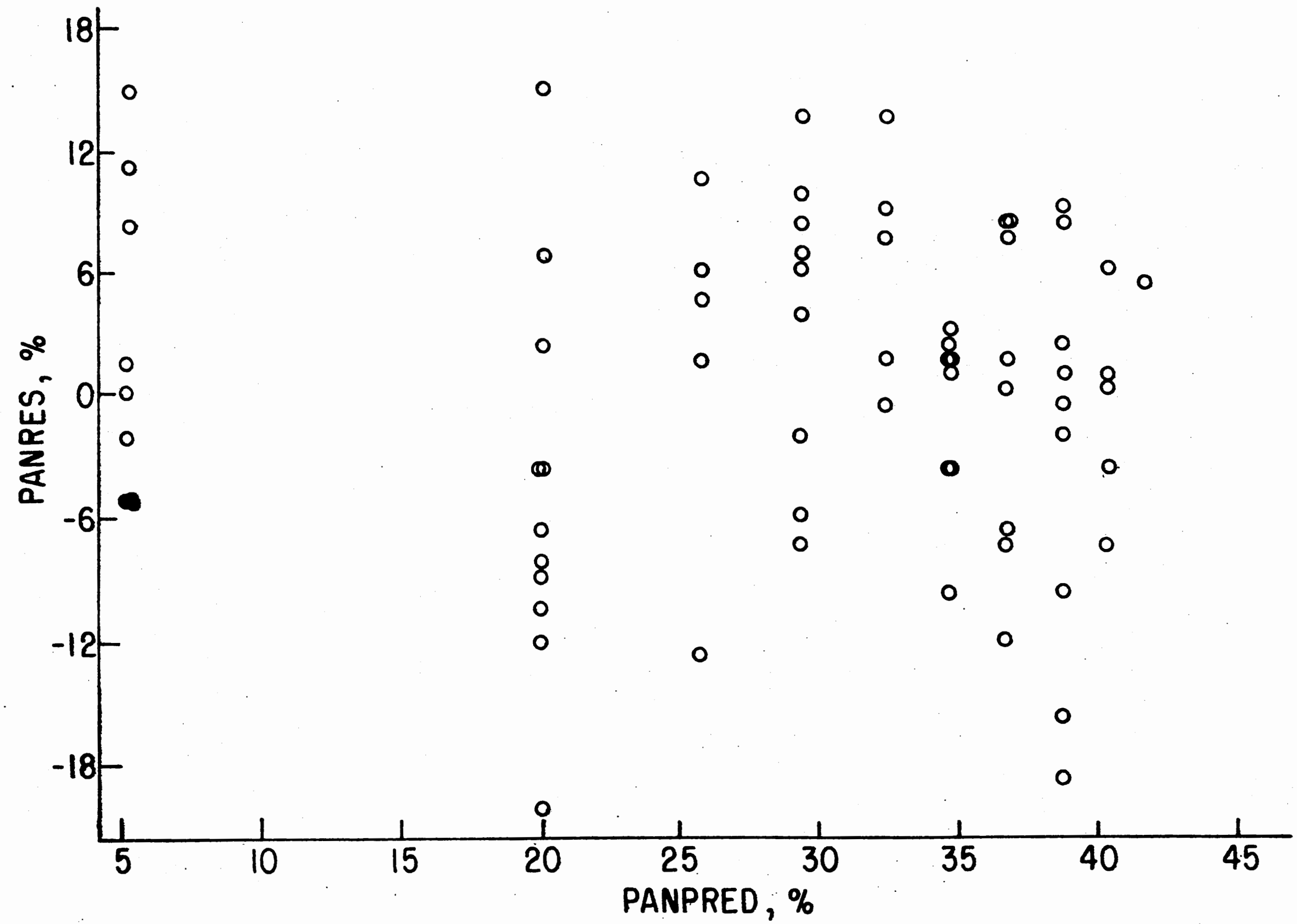

Figure 29. Plot of Residual, PANRES Versus Predicted Evaporation, PANPRED

assumptions that were observed at very low PANEVA values were due to the fact that the point gage used to read the pan evaporation during the tests was not accurate enough to read very small values. A pan evaporation reading device capable of being read to the nearest 0.0030 cm (0.0001 ft) instead of 0.030 cm (0.001 ft) (which was used for the present study) would be recommended for future works in this area. The model's (Equation (5.32)) predicting ability is demonstrated graphically by Figure 30, which is a plot of the predicted EVAP against PANEVA. Although the plotted data appeared to be scattered, the scatter was consistent, indicating that the model would predict EVAP fairly well within the range of its prediction. The model predicted EVAP within -20 and +15 percent of the observed EVAP which seemed to be somewhat wide. It is suspected that use of a not too precise pan evaporation reading device was the reason for such a wide range of prediction.

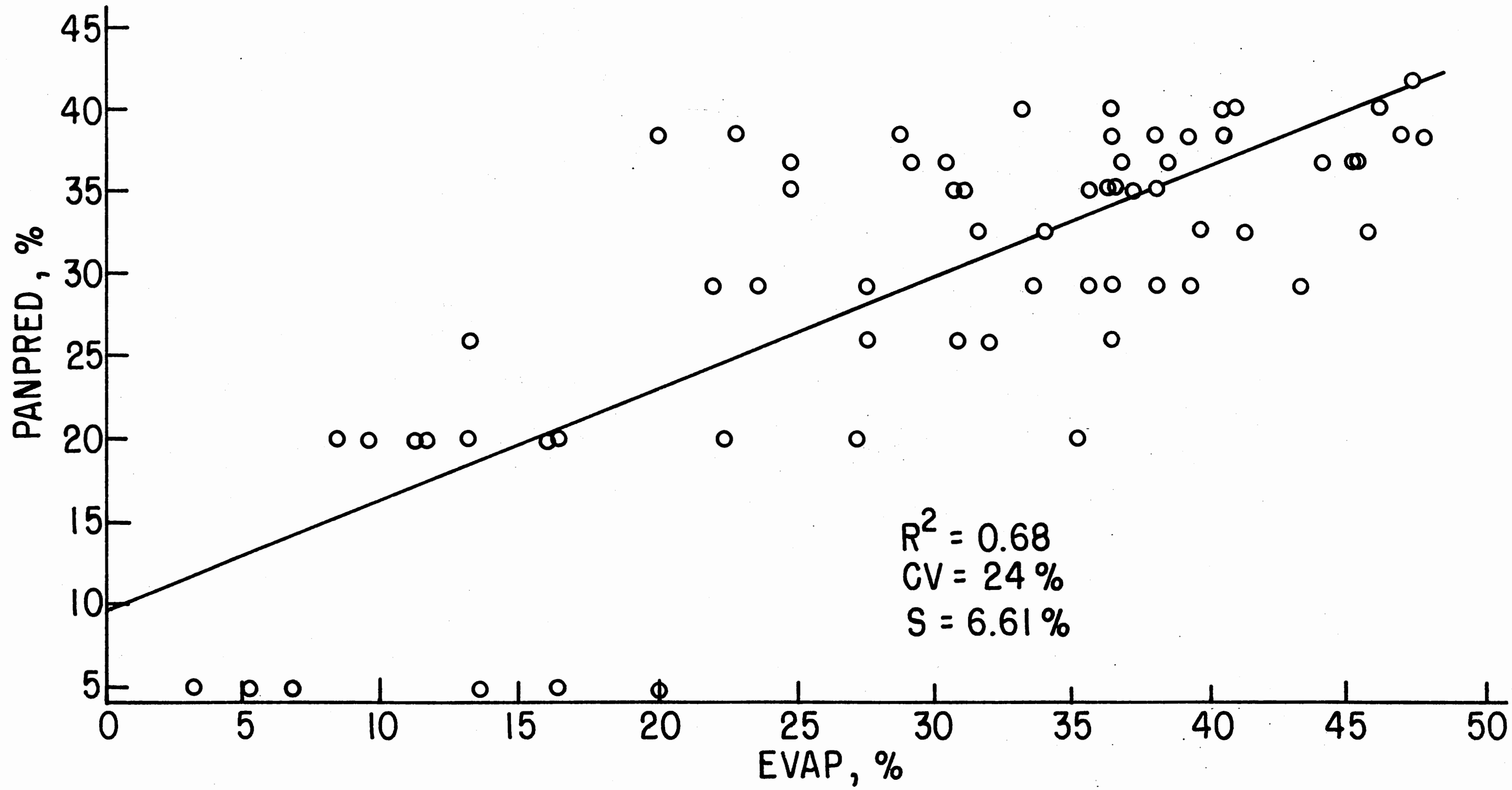

Figure 30. Plot of Predicted Evaporation, PANPRED Versus Observed Evaporation, EVAP

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

This study was conducted with a 7° Trajectory Full Circle Sprinkler primarily to define quantitatively the loss and uniformity characteristics of a center pivot sprinkler irrigation system, among others. A no. 12 sprinkler nozzle (0.48 cm diameter) was used with a 7° LTS to develop empirical models to predict evaporation loss and uniformity of distribution of the sprinkler system. Evaporation loss was considered as the combined loss of evaporation and drift, occurring between the sprinkler nozzle and the ground surface, during operation of the sprinkler. The catch can method was employed using no evaporation suppressant in the cans.

Using data from a 3 x 2^3 factorially arranged single and stationary sprinkler tests in completely randomized design, losses were determined for each test using the following equation:

$$EVAP = \frac{V_{spr} - V_{grd}}{V_{spr}} \times 100 \qquad (5.8)$$

where

EVAP = evaporation from the sprinkler pattern (percent);

V_{spr} = volume of water discharged by the sprinkler (ℓ); and

V_{grd} = volume of water reaching the ground surface (ℓ).

The average evaporation loss ranged from zero to 48 percent under different combinations of test conditions. The computed evaporation losses were found comparable to other researchers (Christiansen, 1942; Clark and Finley, 1975) and to those determined using total runoff from the sprinkler field and were considered suitable for use in developing the evaporation model. The computed evaporation losses along with other operating conditions during each of the 72 tests were utilized to develop the evaporation model using linear regression techniques. With the available data, the best evaporation model was found as:

$$EVAP = 1.45 - 0.34\ RH + 1.16\ T + 0.81\ WS + 0.03\ PRESS \qquad (5.14)$$

with $R^2 = 0.89$, CV = 17 percent, and s = 4.76 percent, and where

EVAP = evaporation from the sprinkler pattern (percent);

RH = relative humidity of the surrounding atmosphere (percent);

T = air temperature (°C);

WS = wind speed (km/hr); and

PRESS = sprinkler operating pressure (kPa).

To demonstrate the effect of pressure and wind on the distribution of water, sprinkler distribution patterns were constructed using three-dimensional graphical procedure. These graphs depicted that low pressure resulted in donut-shaped patterns and wind speed produced distorted patterns. The distortion was pronounced at higher pressure when combined with higher wind speed.

The single stationary distribution pattern was simulated to a moving one and many of the simulated patterns were overlapped by unit increment. Each increment of overlap represented a one-meter move of the pattern to ward a pattern located at the center. Uniformities were computed from the central overlapped pattern using Christiansen's uniformity expression given by:

$$UC = 100 \left[1 - \frac{\Sigma |d - d_{avg}|}{N \cdot d_{avg}}\right] \qquad (2.1)$$

where

UC = Uniformity Coefficient;

d = Depth of water at any grid point;

d_{avg} = Average value of d; and

N = Total number of grid points (observations).

Utilizing the computed uniformities from all the tests, the uniformity model was developed to predict uniformity of water distribution. The available data produced the following model:

$$UC = 79.50 + 8.94 \text{ Log (PRESS)} - 1.16 \text{ SSP} + 0.61 \text{ RHT} \qquad (5.30)$$

with R^2 = 0.52, CV = 2.2 percent, and s = 2.12 percent, and where

UC = uniformity of distribution (percent);

PRESS = sprinkler operating pressure (kPa);

SSP = spacing between sprinklers, m; and

RHT = riser height, m.

Using data from the same 72 tests, an optimum can spacing criterion was established for sprinkler testing purposes. The established criterion was that no cans should represent more than 2.25 percent of the pattern area.

A separate group of nine tests of completely randomized design was conducted to evaluate the effect of using suppressant in the cans to retard evaporation from them. The results indicated a significant effect of the suppressant on evaporation reduction. An average of 11 percent reduction was observed for these tests.

Finally, an empirical relationship between sprinkler evaporation loss and standard pan evaporation was established using evaporation loss results of the 72 tests computed earlier and pan evaporation data recorded during these tests. The relationship would allow one to predict sprinkler loss from pan evaporation records. The established relationship was:

$$EVAP = 37.14 + 11.27 \text{ Log } (PANEVA) + 54.04 \, (PANEVA)^{\frac{1}{2}} \qquad (5.32)$$

with R^2 = 0.68, CV = 29 percent, and s = 8.07 percent, and where EVAP is evaporation from the sprinkler pattern (percent), and PANEVA is evaporation from free water surface in a standard evaporation pan (cm/hr).

Conclusions

Based on the analyses of data and interpretations of the results of this study, the following conclusions were made:

1. The evaporation losses of the 7° LTS ranged from zero to 48 percent under different operating conditions of the system. The results agreed very well with other researchers (Christiansen, 1942; Clark and Finley, 1975), and they were found comparable with those computed using direct runoff data.

2. A four variable linear sprinkler evaporation model was developed using regression techniques. The model was given by:

$$EVAP = 1.45 - 0.34 \, RH + 1.16 \, T + 0.81 \, WS + 0.03 \, PRESS \qquad (5.14)$$

where

EVAP = evaporation from the sprinkler pattern (percent);

RH = relative humidity of the surrounding atmosphere (percent);

T = air temperature (°C);

WS = wind speed (km/hr); and

PRESS = sprinkler operating pressure (kPa).

The model showed an R^2 value of 0.89 and an s value of 4.76; it was adequate (F = 0.0001), and no violations to the assumptions of regression technique were observed. The model predicted evaporation losses within -10 and +8 percent of the actual values. It showed that relative humidity (RH), air temperature (T), wind speed (WS), and operating pressure (PRESS) had an influence on the evaporation loss (EVAP) in order of descending magnitudes. The losses increased with increase in T, WS, and PRESS, and with a decrease in RH. The evaporation model is recommended for conditions under which it was developed.

3. Effect of pressure and wind on the shape of sprinkler distribution patterns was studied using three-dimensional graphical procedures. The graphs demonstrated that low pressures resulted in a donut-shaped pattern; as the pressure was increased to about 414 kPa, a uniform shape was approached. Low wind did not affect the pattern shape; as the wind increased, the uniformity was destroyed, yielding distorted patterns.

4. Using regression techniques, a three variable sprinkler uniformity model was developed which was given by:

$$UC = 79.50 + 8.94 \text{ Log (PRESS)} - 1.16 \text{ SSP} + 0.61 \text{ RHT} \qquad (5.30)$$

where

UC = uniformity of water distribution (percent);

PRESS = sprinkler operating pressure (kPa);

SSP = spacing between sprinklers, m; and

RHT = riser height, m.

The model had a R^2 of 0.52 and an s value of 2.12. Although the model showed a tendency not to conform fully to the regression assumptions, it was adequate (F = 0.0001) and predicted uniformities within -8 and +6 percent of the actual values. It was suspected that speed and uniformity of sprinkler rotation, which was not accounted for, should have been considered in the independent variables list. However, the model established in this work indicated an increase in uniformity with increase in PRESS and RHT and with a decrease in SSP.

5. An optimum can spacing criterion of the catch can method of sprinkler testing was established: The criterion being that no cans should represent more than 2.25 percent of the pattern area, for identifying sprinkler uniformities within ±1.13 percent of the actual values. The criterion is recommended for use in sprinkler testing programs.

6. Use of evaporation suppressant in the cans to retard evaporation from them during the test was found effective. Results from nine tests using suppressant in the cans showed an average of 11 percent reduction in evaporation as compared to tests with no suppressant usage.

7. Finally, a relationship between sprinkler evaporation loss and evaporation from a standard evaporation pan was developed which is:

$$EVAP = 37.14 + 11.27 \text{ Log (PANEVA)} + 54.04 \text{ (PANEVA)}^{\frac{1}{2}} \qquad (5.32)$$

where EVAP is evaporation from the sprinkler pattern (percent), and PANEVA is evaporation from the water surface in a standard evaporation pan (cm/hr). It showed a R^2 value of 0.68 and an s value of 8.07. Although the model produced a wider range of predicted values, from -20 to +15 percent of actual sprinkler loss, it was an adequate model (F = 0.0001), and no significant violation of the regression assumption was observed. Therefore, it can be used for prediction purposes.

Recommendations for Future Research

Based on the experience from the works which constituted this thesis, the following recommendations are made for future considerations:

1. Perform extensive tests including at least three riser heights and three levels of air temperature, and speed and uniformity of sprinkler rotation in addition to the variables already considered in this study; then determine the accuracy and validity of the evaporation and uniformity models already developed in this study.

2. Conduct a series of factorially arranged tests to determine the effect of suppressant usage in cans on evaporation reduction to strengthen or modify the conclusions made in this work.

3. Use a pan evaporation measuring device capable of being read to the nearest 0.0030 cm (0.0001 ft) and develop a relationship between sprinkler evaporation and pan evaporation loss; then determine the validity of the relationship already developed in this work.

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APPENDIX A

ANALYSES OF VARIANCE FOR DIFFERENT EVAPORATION MODELS IN ORIGINAL VARIABLES

STATISTICAL ANALYSIS SYSTEM

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE EVAP

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB > F	R-SQUARE	C.V.
REGRESSION	1	10153.69880606	10153.69880606	182.14789	0.0001	0.72238515	26.94847 %
ERROR	70	3902.09792194	55.74425603			STD DEV	EVAP MEAN
CORRECTED TOTAL	71	14055.79672800				7.46620761	27.70550

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB > F	PARTIAL SS	F VALUE	PROB > F
RH	1	10153.69880606	182.14789	0.0001	10153.69880606	182.14789	0.0001

SOURCE	B VALUES	T FOR H0: B=0	PROB > |T|	STD ERR B	STD B VALUES
INTERCEPT	69.27451173	21.62620	0.0001	3.20326825	0.0
RH	-0.66865699	-13.49622	0.0001	0.04954403	-0.84993244

STATISTICAL ANALYSIS SYSTEM

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE EVAP

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB > F	R-SQUARE	C.V.
REGRESSION	2	10976.62088912	5488.31044455	122.98532	0.0001	0.78093196	24.11164 %
ERROR	69	3079.17583888	44.62573680			STD DEV	EVAP MEAN
CORRECTED TOTAL	71	14055.79672800				6.68024976	27.70550

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB > F	PARTIAL SS	F VALUE	PROB > F
RH	1	10153.69880606	227.53011	0.0001	2101.07488855	47.08213	0.0001
T	1	822.92208305	18.44053	0.0001	822.92208305	18.44053	0.0001

SOURCE	B VALUES	T FOR H0: B=0	PROB > |T|	STD ERR B	STD B VALUES
INTERCEPT	25.02989753	2.34046	0.0222	10.69444011	0.0
RH	-0.45602219	-6.86164	0.0001	0.06645963	-0.57965154
T	1.10048072	4.29424	0.0001	0.25626883	0.36276518

STATISTICAL ANALYSIS SYSTEM

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE EVAP

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB > F	R-SQUARE	C.V.
REGRESSION	3	11911.41053176	3970.47017725	125.90641	0.0001	0.84743759	20.26894 %
ERROR	68	2144.38619624	31.53509112			STD DEV	EVAP MEAN
CORRECTED TOTAL	71	14055.79672800				5.61561138	27.70550

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB > F	PARTIAL SS	F VALUE	PROB > F
RH	1	10153.69880606	321.98096	0.0001	861.09330930	27.30588	0.0001
T	1	822.92208305	26.09544	0.0001	1019.34323829	32.32409	0.0001
WS	1	934.78964264	29.64284	0.0001	934.78964264	29.64284	0.0001

SOURCE	B VALUES	T FOR H0:B=0	PROB > |T|	STD ERR B	STD B VALUES
INTERCEPT	5.79727406	0.60018	0.5504	9.55916456	0.0
RH	-0.31985522	-5.22550	0.0001	0.06121042	-0.40656919
T	1.23253281	5.68543	0.0001	0.21678804	0.40629515
WS	0.79909858	5.44452	0.0001	0.14677107	0.29517972

STATISTICAL ANALYSIS SYSTEM

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE EVAP

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB > F	R-SQUARE	C.V.
REGRESSION	5	12764.42515100	2552.83503020	130.47400	0.0001	0.90812534	15.96569 %
ERROR	66	1291.37157700	19.56623602			STD DEV	EVAP MEAN
CORRECTED TOTAL	71	14055.79672800				4.42337383	27.70550

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB > F	PARTIAL SS	F VALUE	PROB > F
RH	1	10153.69880606	518.93981	0.0001	1162.80378687	59.42936	0.0001
T	1	822.92208305	42.05827	0.0001	349.09764869	17.84184	0.0001
WS	1	934.78964264	47.77565	0.0001	1041.10952408	53.20949	0.0001
PRESS	1	623.32766261	31.85731	0.0001	656.45032795	33.55016	0.0001
RHT	1	229.68695663	11.73894	0.0011	229.63695663	11.73894	0.0011

SOURCE	B VALUES	T FOR H0:B=0	PROB > |T|	STD ERR B	STD B VALUES
INTERCEPT	7.95025202	1.00902	0.3166	7.87917731	0.0
RH	-0.39847693	-7.70904	0.0001	0.05168954	-0.50650555
T	0.83079408	4.22396	0.0001	0.19668606	0.27386501
WS	0.84825095	7.29448	0.0001	0.11628663	0.31333615
PRESS	0.02692351	5.79225	0.0001	0.00464820	0.21696460
RHT	2.71425387	3.42621	0.0011	0.79220202	0.14861082

APPENDIX B

ANALYSES OF VARIANCE FOR DIFFERENT EVAPORATION MODELS IN TRANSFORMED VARIABLES

STATISTICAL ANALYSIS SYSTEM

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE YEVA4

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB > F	R-SQUARE	C.V.
REGRESSION	1	182.19794913	182.19794913	174.39036	0.0001	0.71357299	20.79548 %
ERROR	70	73.13395239	1.04477075			STD DEV	YEVA4 MEAN
CORRECTED TOTAL	71	255.33190152				1.02214028	4.91520

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB > F	PARTIAL SS	F VALUE	PROB > F
X13	1	182.19794913	174.39036	0.0001	182.19794913	174.39036	0.0001

SOURCE	B VALUES	T FOR H0:B=0	PROB > |T|	STD ERR B	STD B VALUES
INTERCEPT	7.72685909	31.58628	0.0001	0.24462703	0.0
X13	-0.00067260	-13.20569	0.0001	0.00005093	-0.84473250

STATISTICAL ANALYSIS SYSTEM

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE YEVA4

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB > F	R-SQUARE	C.V.
REGRESSION	2	203.23975041	101.61987520	134.60322	0.0001	0.79598260	17.67747 %
ERROR	69	52.09215111	0.75495871			STD DEV	YEVA4 MEAN
CORRECTED TOTAL	71	255.33190152				0.86888360	4.91520

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB > F	PARTIAL SS	F VALUE	PROB > F
X13	1	182.19794913	241.33498	0.0001	183.08290095	242.50717	0.0001
X2	1	21.04180127	27.87146	0.0001	21.04180127	27.87146	0.0001

SOURCE	B VALUES	T FOR H0:B=0	PROB > |T|	STD ERR B	STD B VALUES
INTERCEPT	1.15040473	0.91090	0.3655	1.26293318	0.0
X13	-0.00067425	-15.57264	0.0001	0.00004330	-0.84680352
X2	2.74426441	5.27934	0.0001	0.51981176	0.28707820

STATISTICAL ANALYSIS SYSTEM

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE YEVA4

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB > F	R-SQUARE	C.V.
REGRESSION	3	219.34859282	73.11619761	138.17244	0.0001	0.85907241	14.79976 %
ERROR	68	35.98330870	0.52916630			STD DEV	YEVA4 MEAN
CORRECTED TOTAL	71	255.33190152				0.72743818	4.91520

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB > F	PARTIAL SS	F VALUE	PROB > F
X13	1	182.15794913	344.31132	0.0001	70.91076993	134.00470	0.0001
X2	1	21.04180127	39.75406	0.0001	19.79274443	37.40364	0.0001
X9	1	16.10884241	30.44193	0.0001	16.10884241	30.44193	0.0001

SOURCE	B VALUES	T FOR H0: B=0	PROB > |T|	STD ERR B	STD B VALUES
INTERCEPT	-0.95385793	-0.84861	0.3991	1.12402118	0.0
X13	-0.00052437	-11.57604	0.0001	0.00004530	-0.65855672
X2	2.66308820	6.11585	0.0001	0.43544031	0.27858634
X9	0.59745106	5.51742	0.0001	0.10828449	0.31396171

STATISTICAL ANALYSIS SYSTEM

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE YEVA4

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB > F	R-SQUARE	C.V.
REGRESSION	5	229.81618178	45.96323636	118.89038	0.0001	0.90006842	12.65000 %
ERROR	66	25.51571974	0.38660181			STD DEV	YEVA4 MEAN
CORRECTED TOTAL	71	255.33190152				0.62177312	4.91520

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB > F	PARTIAL SS	F VALUE	PROB > F
X13	1	182.19794913	471.28064	0.0001	16.96460868	43.88135	0.0001
X2	1	21.04180127	54.42758	0.0001	18.78824707	48.59845	0.0001
X9	1	16.10884241	41.66779	0.0001	19.35082501	50.07950	0.0001
X18	1	8.39228584	21.70783	0.0001	3.17815003	8.22073	0.0056
RHT	1	2.07530312	5.36806	0.0236	2.07530312	5.36806	0.0236

SOURCE	B VALUES	T FOR H0:B=0	PROB > |T|	STD ERR B	STD B VALUES
INTERCEPT	-3.33269603	-3.05109	0.0033	1.09229722	0.0
X13	-0.00039139	-6.62430	0.0001	0.00005908	-0.49155015
X2	2.59871747	6.97126	0.0001	0.37277594	0.27185250
X9	0.66117370	7.07669	0.0001	0.09342984	0.34744809
X18	0.00148290	2.86718	0.0056	0.00051720	0.19864624
RHT	0.25770845	2.31692	0.0236	0.11122946	0.10468966

APPENDIX C

ANALYSES OF VARIANCE FOR DIFFERENT UNIFORMITY MODELS IN ORIGINAL VARIABLES

STATISTICAL ANALYSIS SYSTEM

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE UC

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB > F	R-SQUARE	C.V.
REGRESSION	1	469.08563293	469.08563293	61.69115	0.0001	0.18883632	2.83901 %
ERROR	265	2015.00025920	7.60377456			STD DEV	UC MEAN
CORRECTED TOTAL	266	2484.08589214				2.75749425	97.12876

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB > F	PARTIAL SS	F VALUE	PROB > F
PRESS	1	469.08563293	61.69115	0.0001	469.08563293	61.69115	0.0001

SOURCE	B VALUES	T FOR H0:B=0	PROB > |T|	STD ERR B	STD B VALUES
INTERCEPT	93.76105572	203.48413	0.0001	0.46077841	0.0
PRESS	0.01181238	7.85437	0.0001	0.00150392	0.43455301

STATISTICAL ANALYSIS SYSTEM

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE UC

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB > F	R-SQUARE	C.V.
REGRESSION	2	1187.61911753	593.80955877	120.91766	0.0001	0.47809100	2.28155 %
ERROR	264	1296.46677461	4.91085899			STD DEV	UC MEAN
CORRECTED TOTAL	266	2484.08589214				2.21604580	97.12876

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB > F	PARTIAL SS	F VALUE	PROB > F
PRESS	1	469.08563293	95.52008	0.0001	725.61513499	147.75727	0.0001
SSP	1	718.53348460	146.31523	0.0001	718.53348460	146.31523	0.0001

SOURCE	B VALUES	T FOR H0:B=0	PROB > |T|	STD ERR B	STD B VALUES
INTERCEPT	98.55427554	181.71673	0.0001	0.54235112	0.0
PRESS	0.01504666	12.15554	0.0001	0.00123784	0.55353585
SSP	-1.24467835	-12.09608	0.0001	0.10289929	-0.55082811

STATISTICAL ANALYSIS SYSTEM

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE UC

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB > F	R-SQUARE	C.V.
REGRESSION	3	1240.87506711	413.62502237	87.50196	0.0001	0.49952986	2.23845 %
ERROR	263	1243.21082503	4.72703736			STD DEV	UC MEAN
CORRECTED TOTAL	266	2484.08585214				2.17417510	97.12876

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB > F	PARTIAL SS	F VALUE	PROB > F
PRESS	1	469.08563293	99.23459	0.0001	705.99696044	149.56450	0.0001
SSP	1	718.53349460	152.00504	0.0001	551.31224412	116.62955	0.0001
RHT	1	53.25594958	11.26624	0.0009	53.25594958	11.26624	0.0009

SOURCE	B VALUES	T FOR H0:B=0	PROB > |T|	STD ERR B	STD B VALUES
INTERCEPT	96.76141390	128.33906	0.0001	0.75395142	0.0
PRESS	0.01486682	12.22966	0.0001	0.00121564	0.54691977
SSP	-1.14056593	-10.79952	0.0001	0.10561269	-0.50475351
RHT	0.61243548	3.35652	0.0009	0.18246131	0.15321162

APPENDIX D

ANALYSES OF VARIANCE FOR DIFFERENT UNIFORMITY MODELS IN TRANSFORMED VARIABLES

STATISTICAL ANALYSIS SYSTEM

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE UC

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB > F	R-SQUARE	C.V.
REGRESSION	1	509.03608967	509.03608967	68.29932	0.0001	0.20491888	2.81072 %
ERROR	265	1975.04980247	7.45301812			STD DEV	UC MEAN
CORRECTED TOTAL	266	2484.08589214				2.73002163	97.12876

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB > F	PARTIAL SS	F VALUE	PROB > F
X6	1	509.03608967	68.29932	0.0001	509.03608967	68.29932	0.0001

SOURCE	B VALUES	T FOR H0:B=0	PROB > |T|	STD ERR B	STD B VALUES
INTERCEPT	79.99554624	38.46178	0.0001	2.07987141	0.0
X6	7.09440978	8.26434	0.0001	0.85843630	0.45267966

STATISTICAL ANALYSIS SYSTEM

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT FOR DEPENDENT VARIABLE UC

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB > F	R-SQUARE	C.V.
REGRESSION	2	1247.81634515	623.90817258	133.23288	0.0001	0.50232415	2.22796 %
ERROR	264	1236.26954699	4.68283919			STD DEV	UC MEAN
CORRECTED TOTAL	266	2484.08589214				2.16398687	97.12876

SOURCE	DF	SEQUENTIAL SS	F VALUE	PROB > F	PARTIAL SS	F VALUE	PROB > F
X6	1	509.03608957	108.70245	0.0001	785.81236261	167.80682	0.0001
SSP	1	738.78025549	157.76332	0.0001	738.78025549	157.76332	0.0001

SOURCE	B VALUES	T FOR H0:B=0	PROB > |T|	STD ERR B	STD B VALUES
INTERCEPT	81.09982283	49.12225	0.0001	1.65097944	0.0
X6	9.04010375	12.95403	0.0001	0.69786049	0.57683038
SSP	-1.26382629	-12.56039	0.0001	0.10062001	-0.55930196

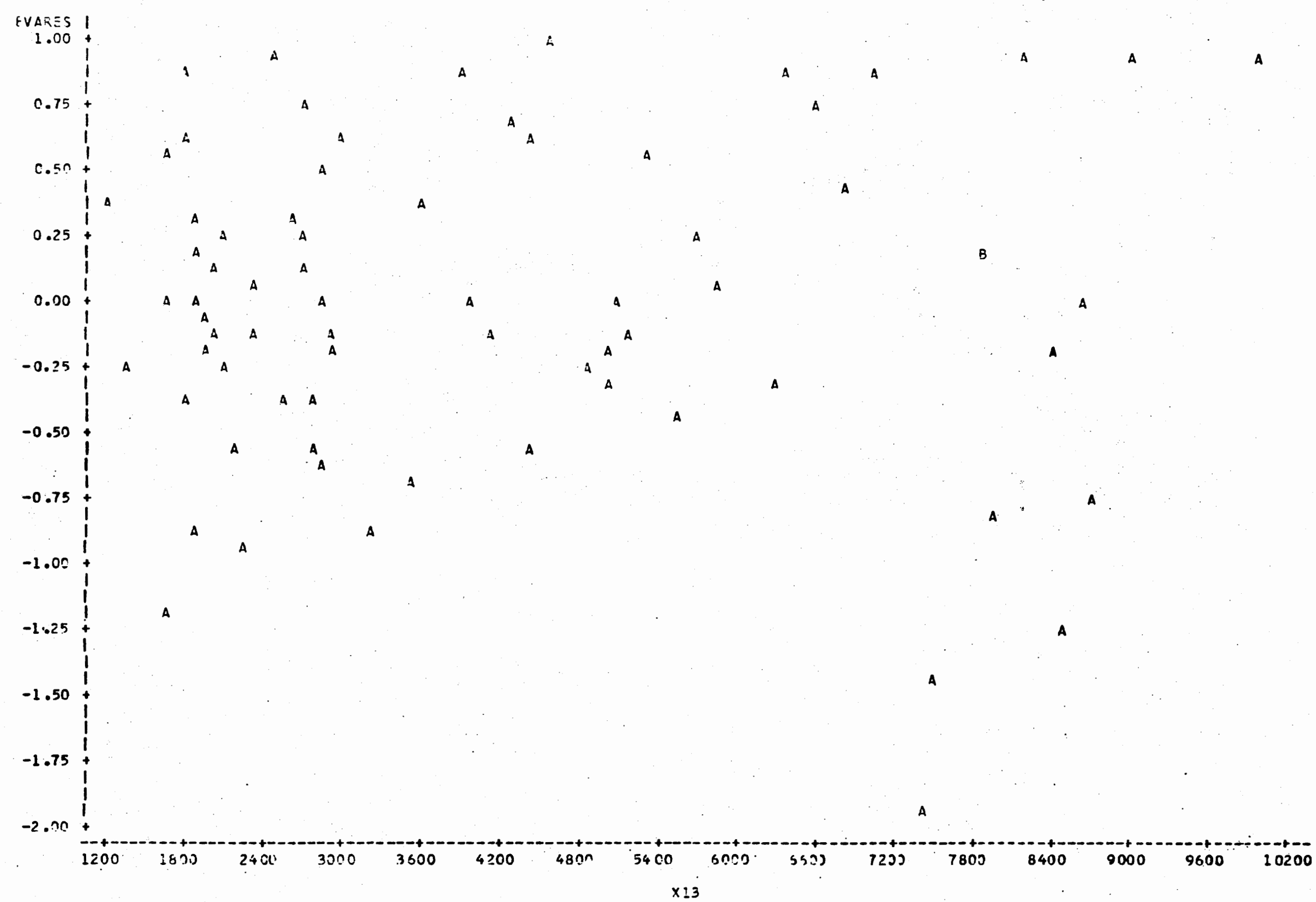
APPENDIX E

PLOTS OF EVAPORATION MODEL IN

TRANSFORMED VARIABLES

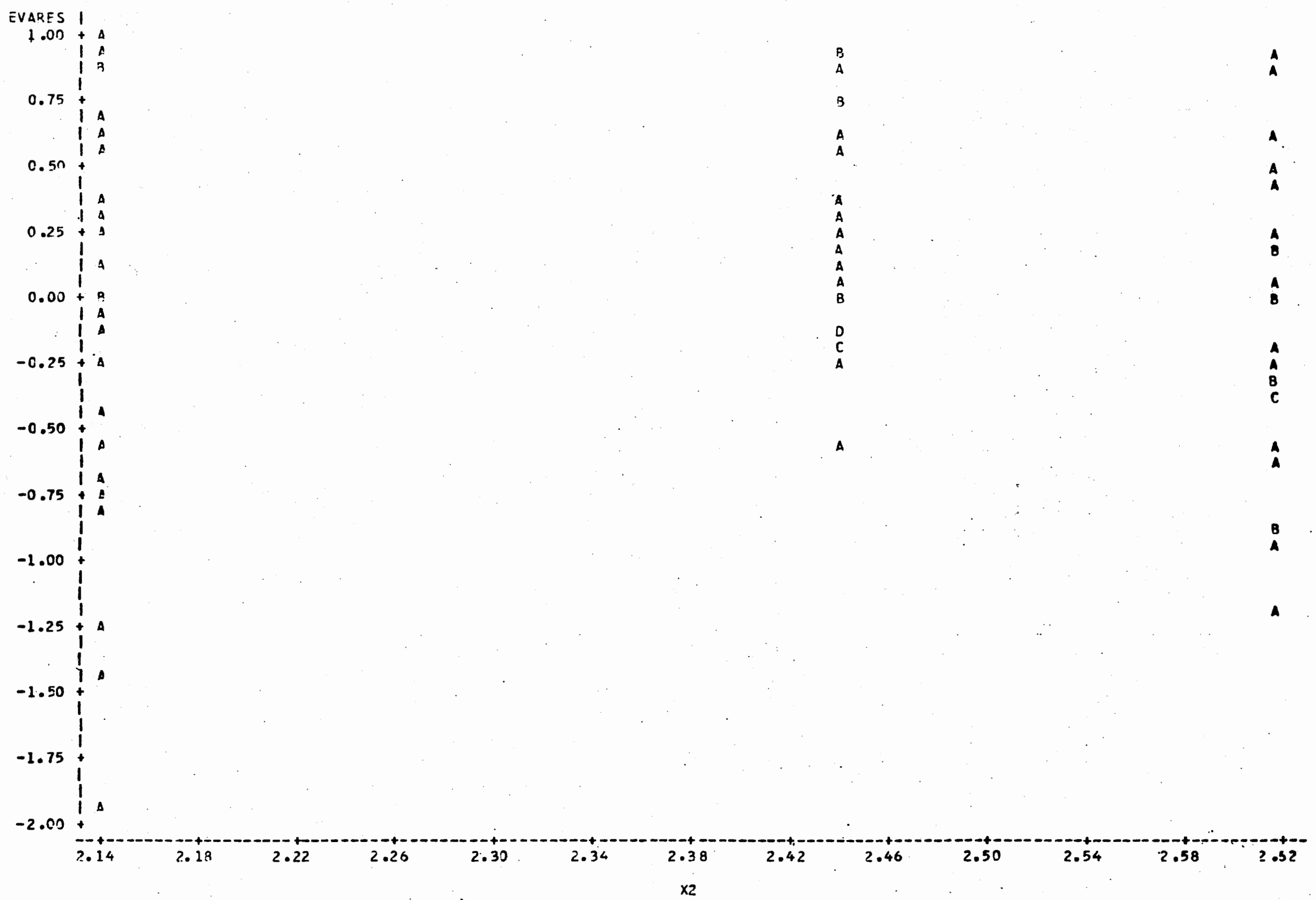
STATISTICAL ANALYSIS SYSTEM

PLOT OF EVARES *X13 LEGEND: A = 1 OBS, B = 2 OBS, ETC.



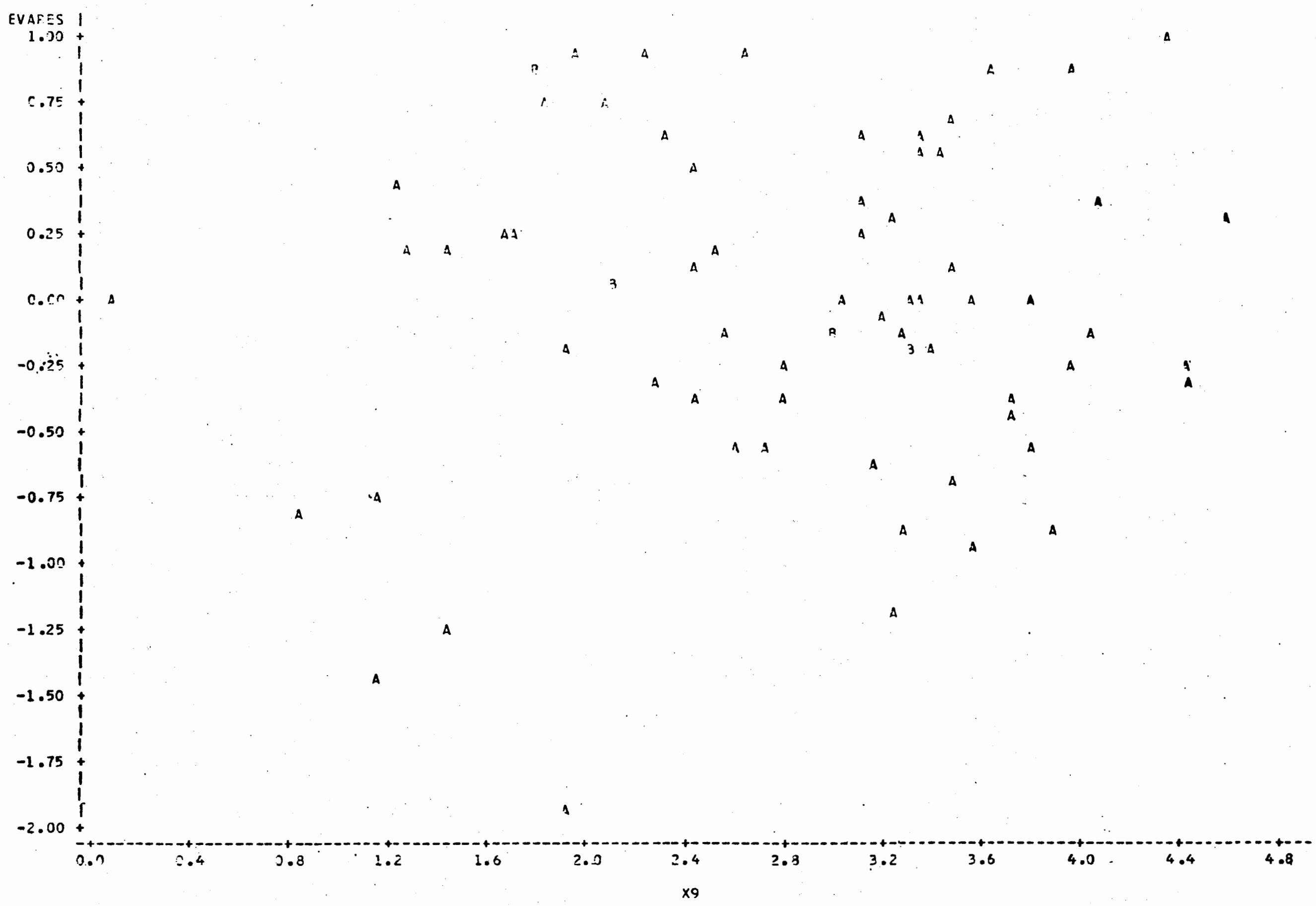
STATISTICAL ANALYSIS SYSTEM

PLOT OF EVARES*X2   LEGEND: A = 1 OBS, B = 2 OBS, ETC.



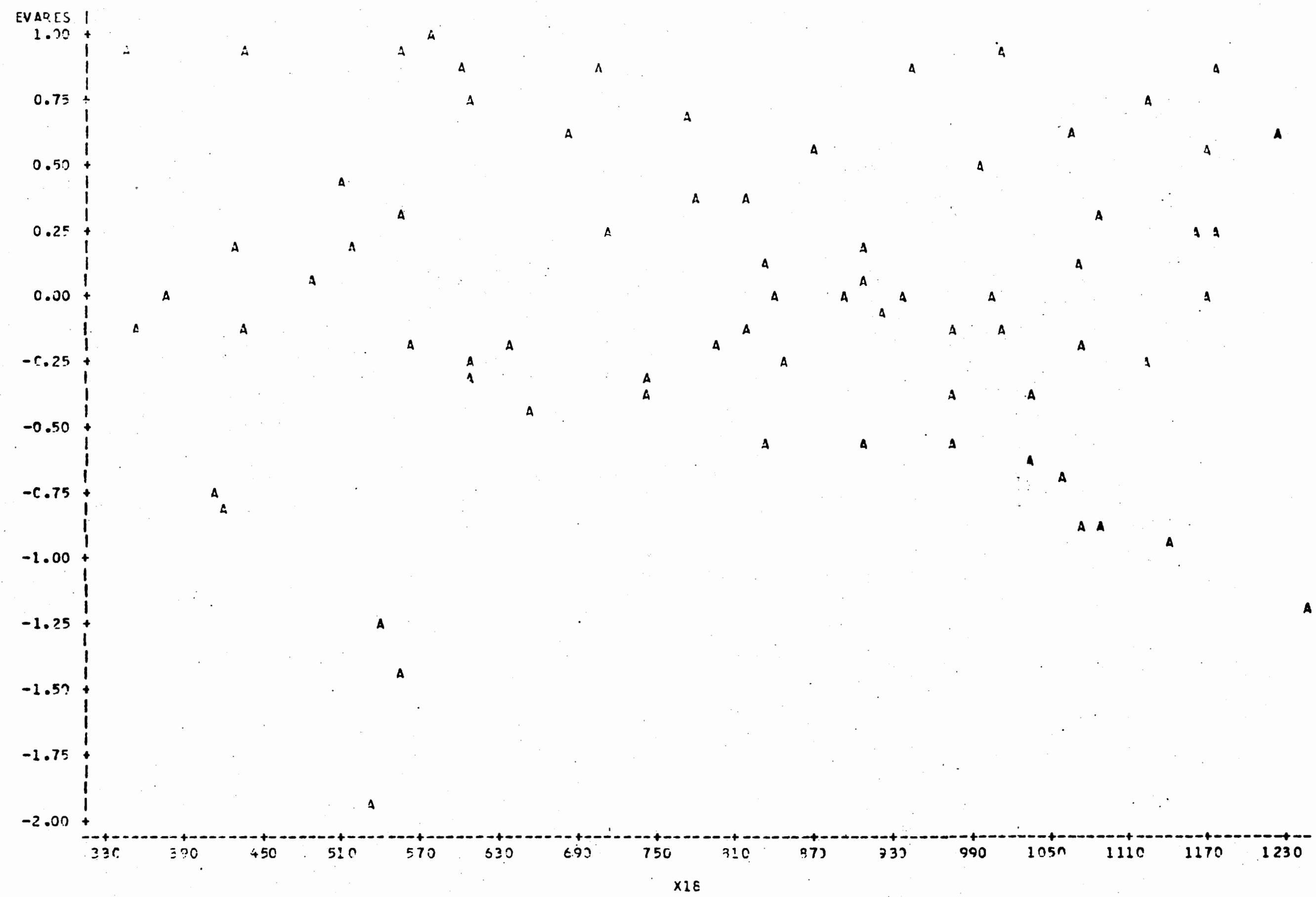
STATISTICAL ANALYSIS SYSTEM

PLOT OF EVARES*X9 LEGEND: A = 1 OBS, B = 2 OBS, ETC.



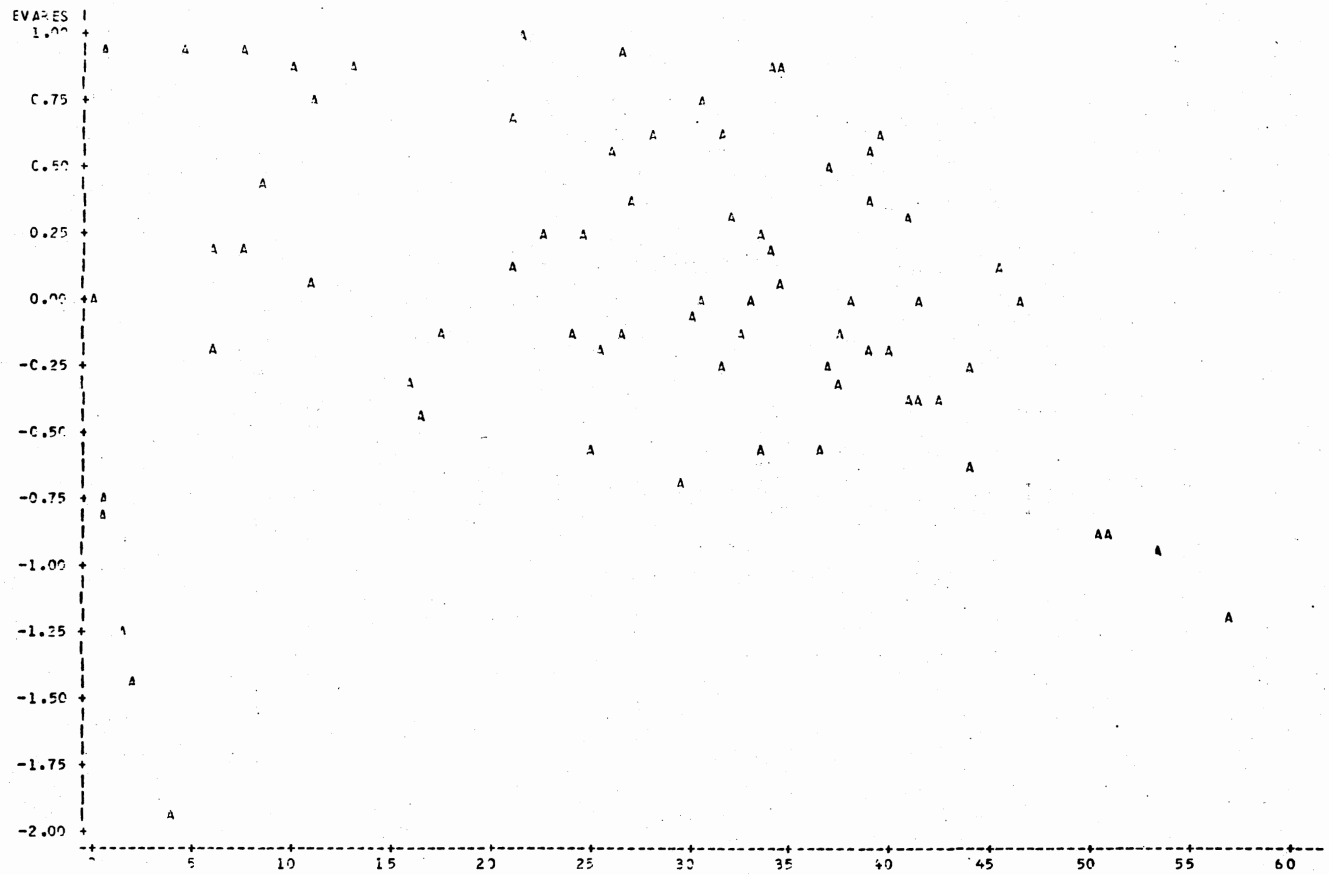
STATISTICAL ANALYSIS SYSTEM

PLOT OF EVARES*X18 LEGEND: A = 1 OBS, B = 2 OBS, ETC.



STATISTICAL ANALYSIS SYSTEM

PLOT OF EVARES*YEVA5 LEGEND: A = 1 OBS, B = 2 OBS, ETC.

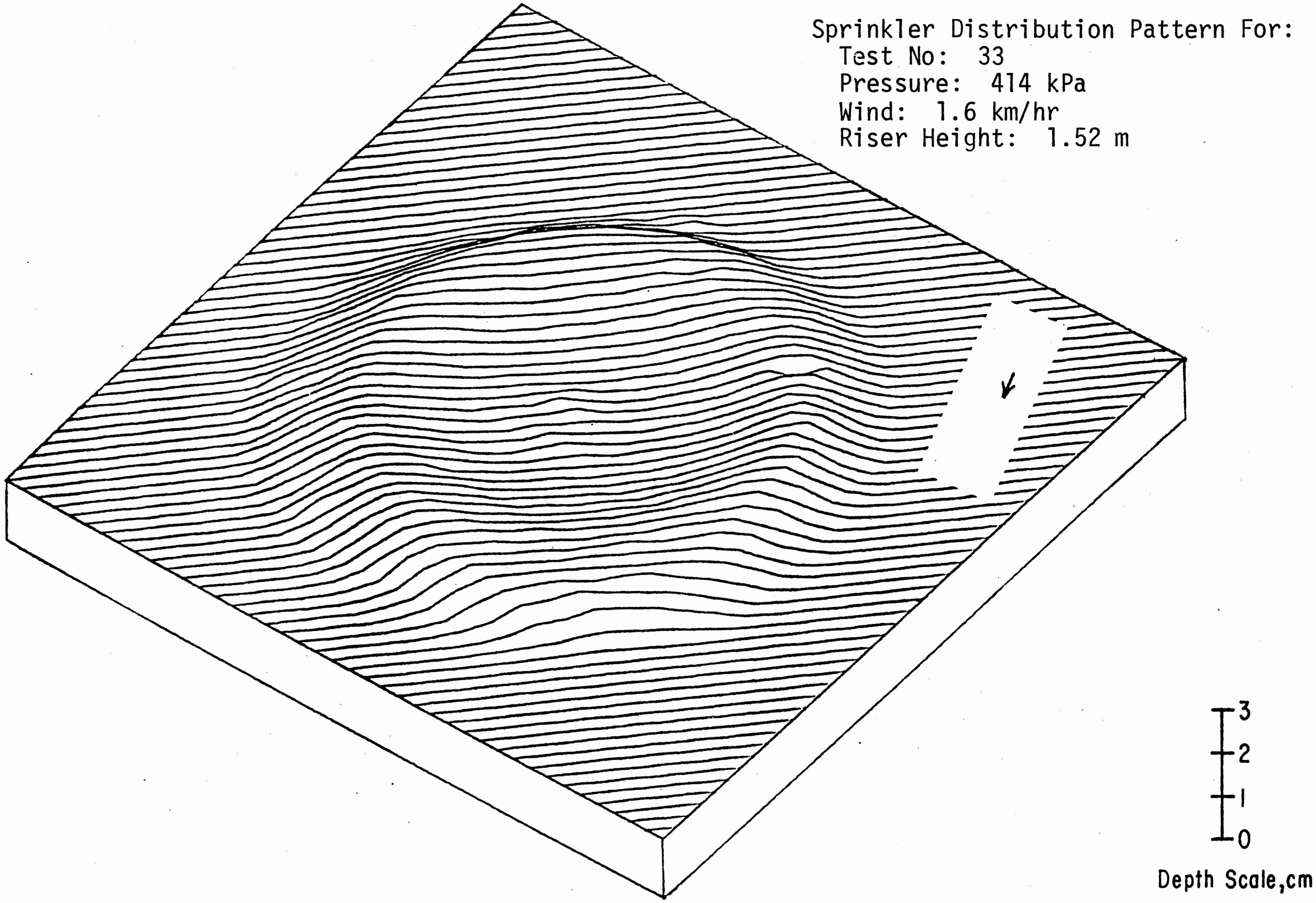


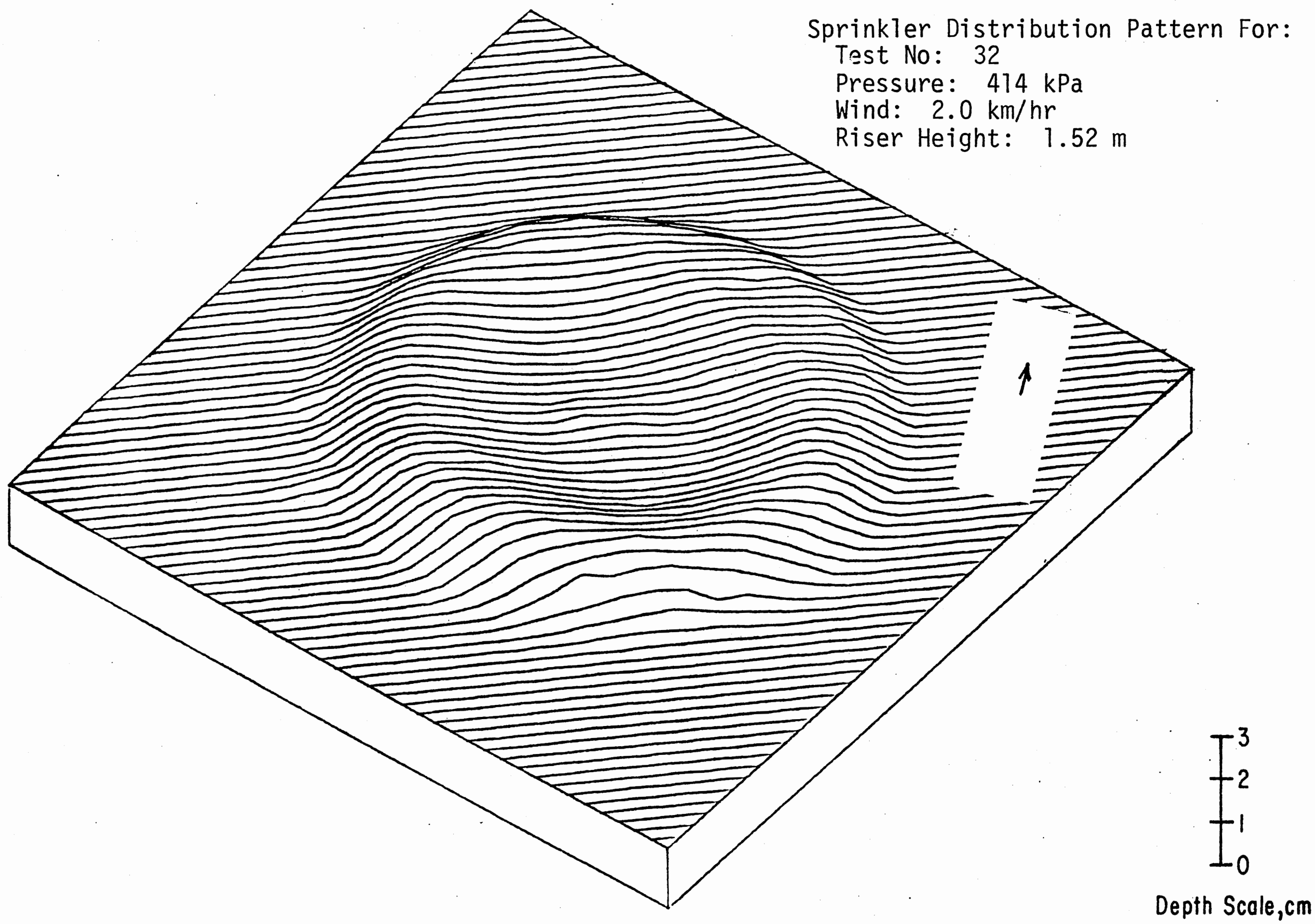
YEVA5 = EVAPRED

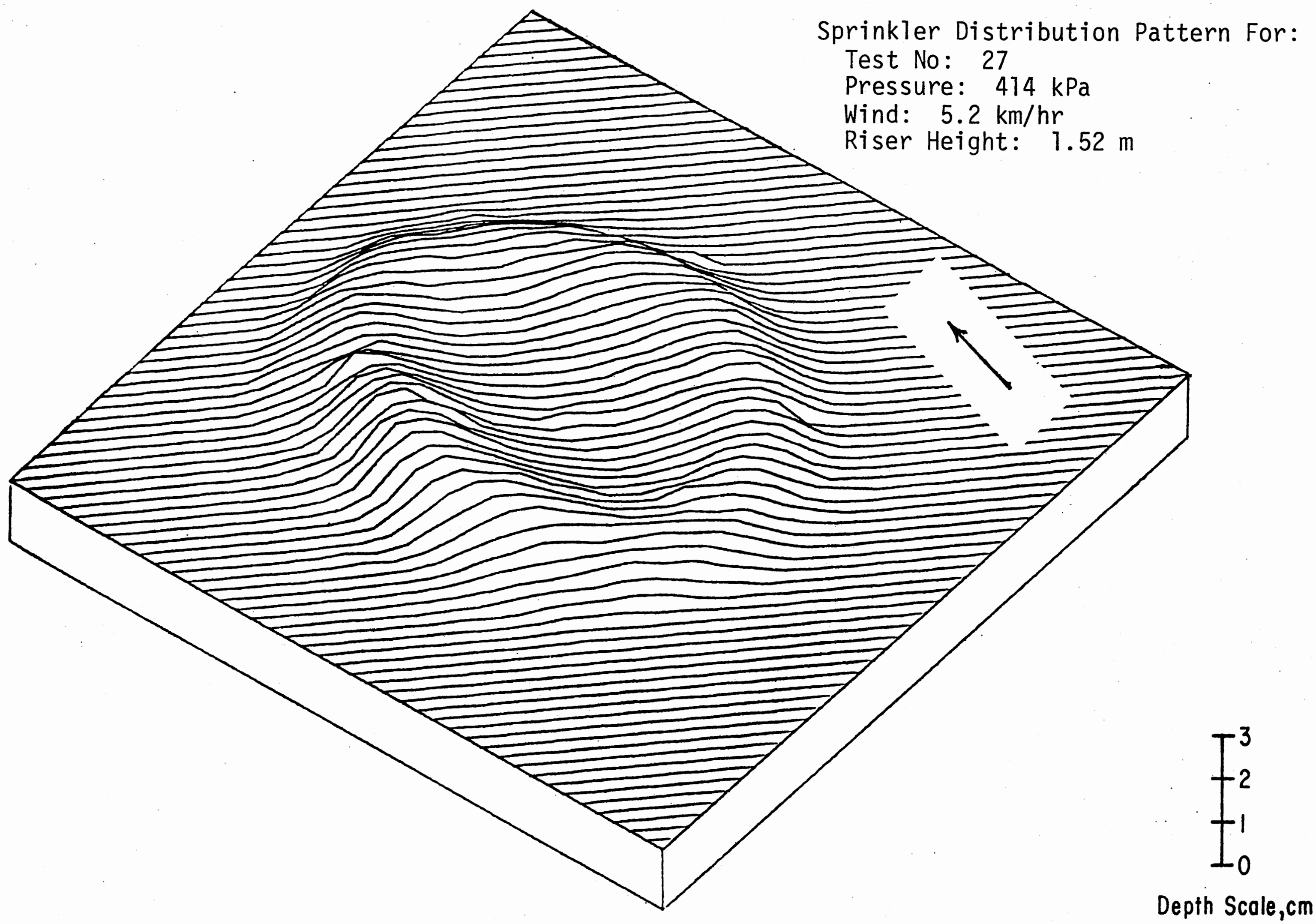
APPENDIX F

SPRINKLER DISTRIBUTION PATTERNS

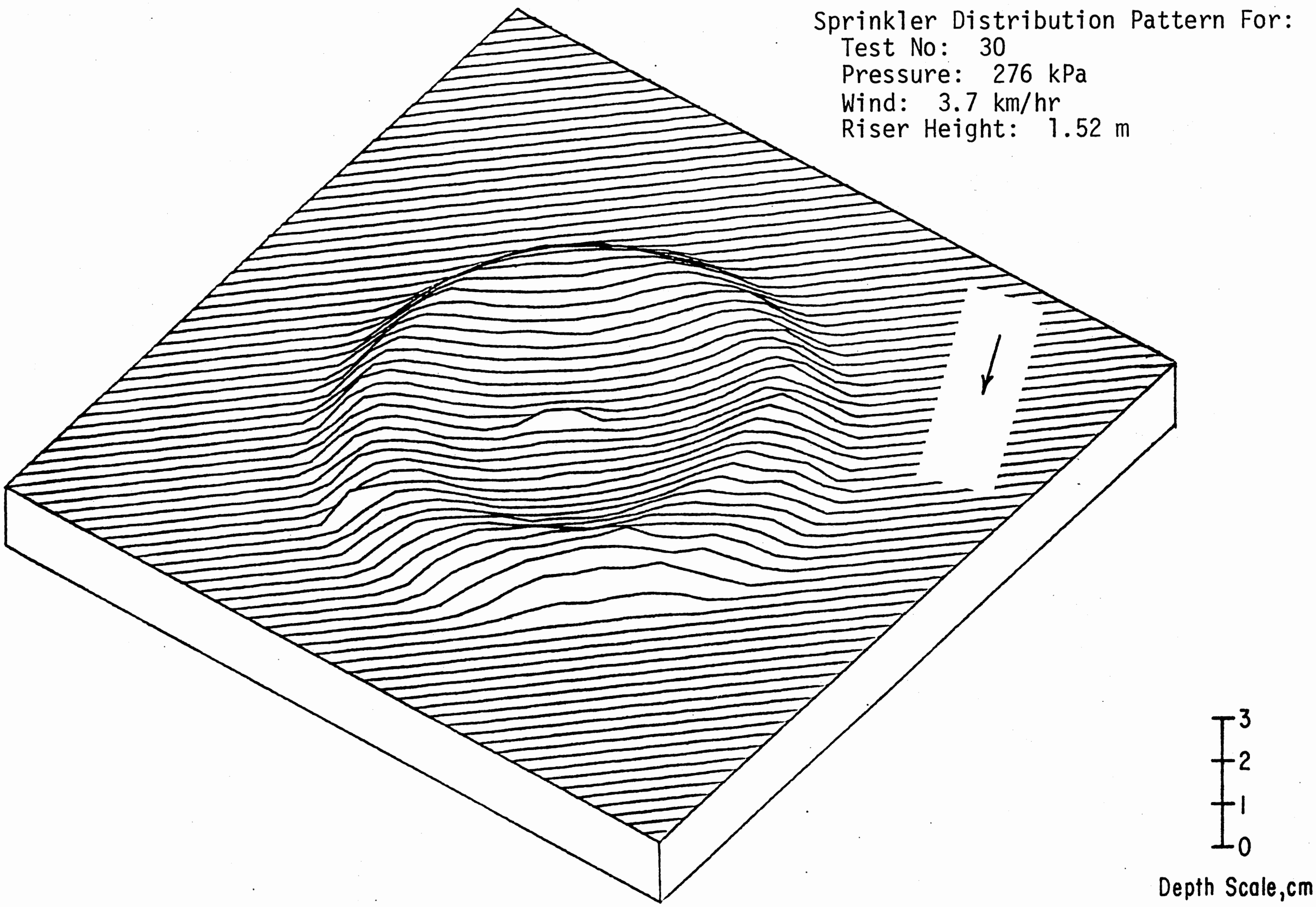
Sprinkler Distribution Pattern For:
Test No: 33
Pressure: 414 kPa
Wind: 1.6 km/hr
Riser Height: 1.52 m

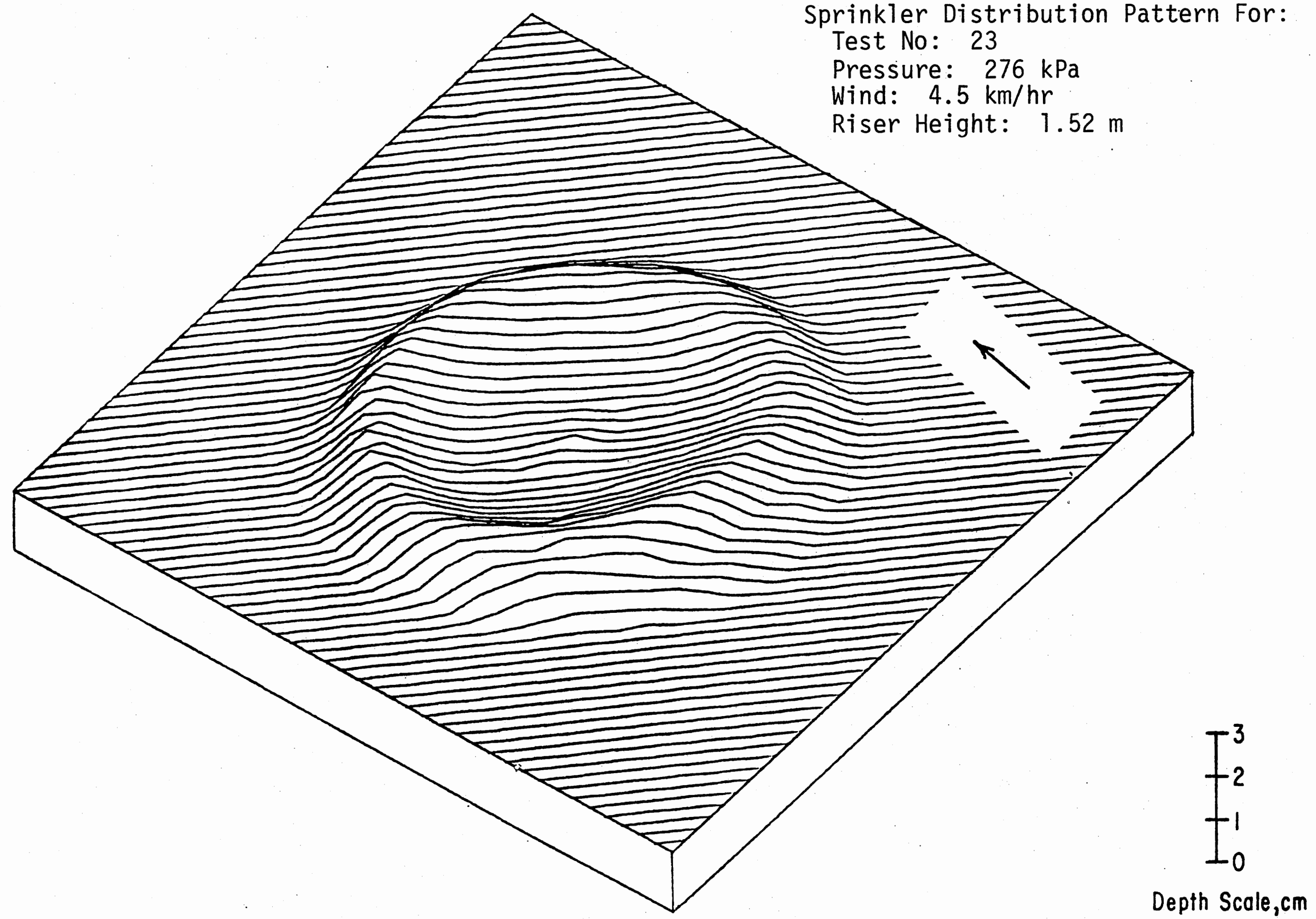


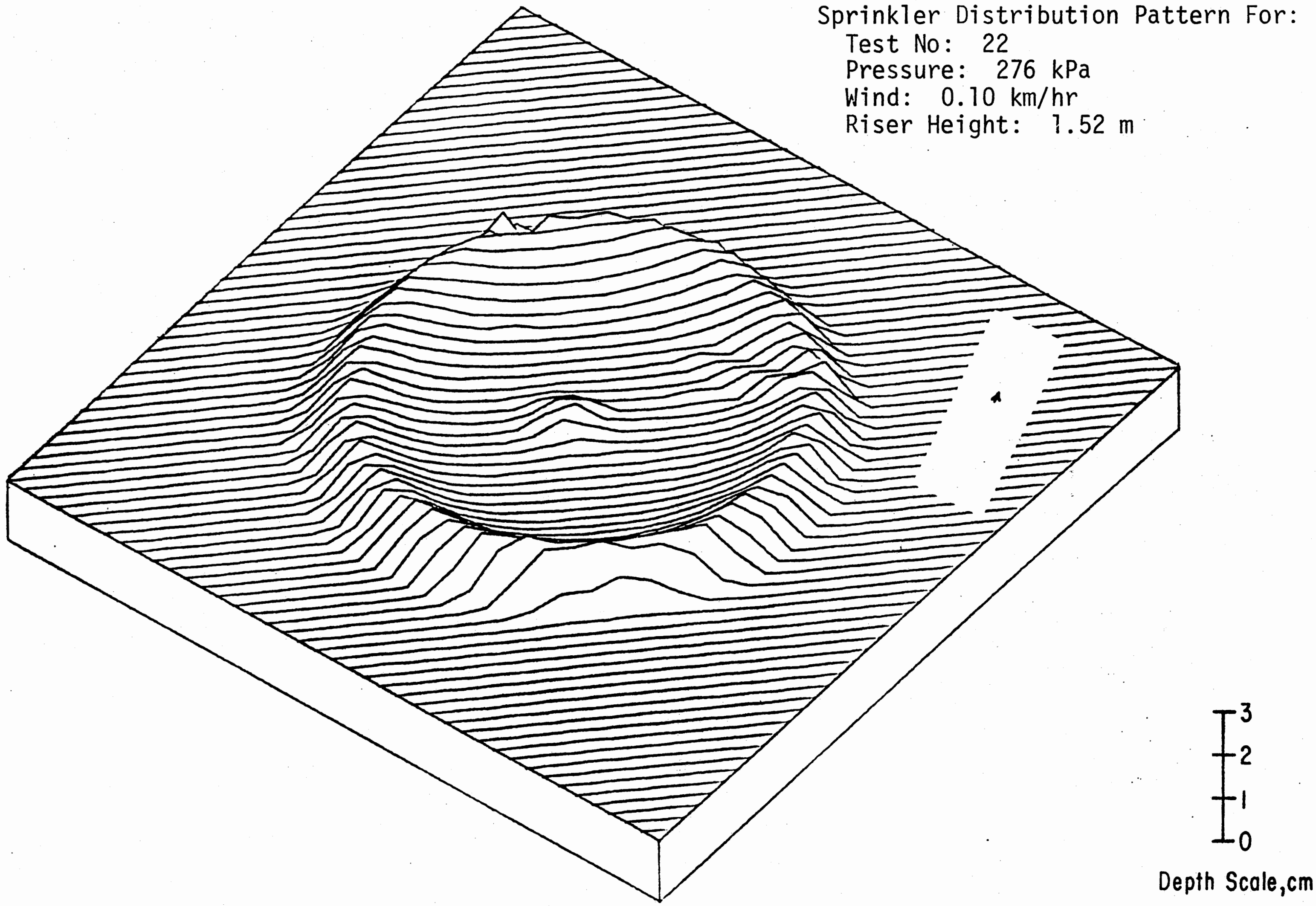

Sprinkler Distribution Pattern For:
Test No: 32
Pressure: 414 kPa
Wind: 2.0 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm


Sprinkler Distribution Pattern For:
Test No: 27
Pressure: 414 kPa
Wind: 5.2 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm

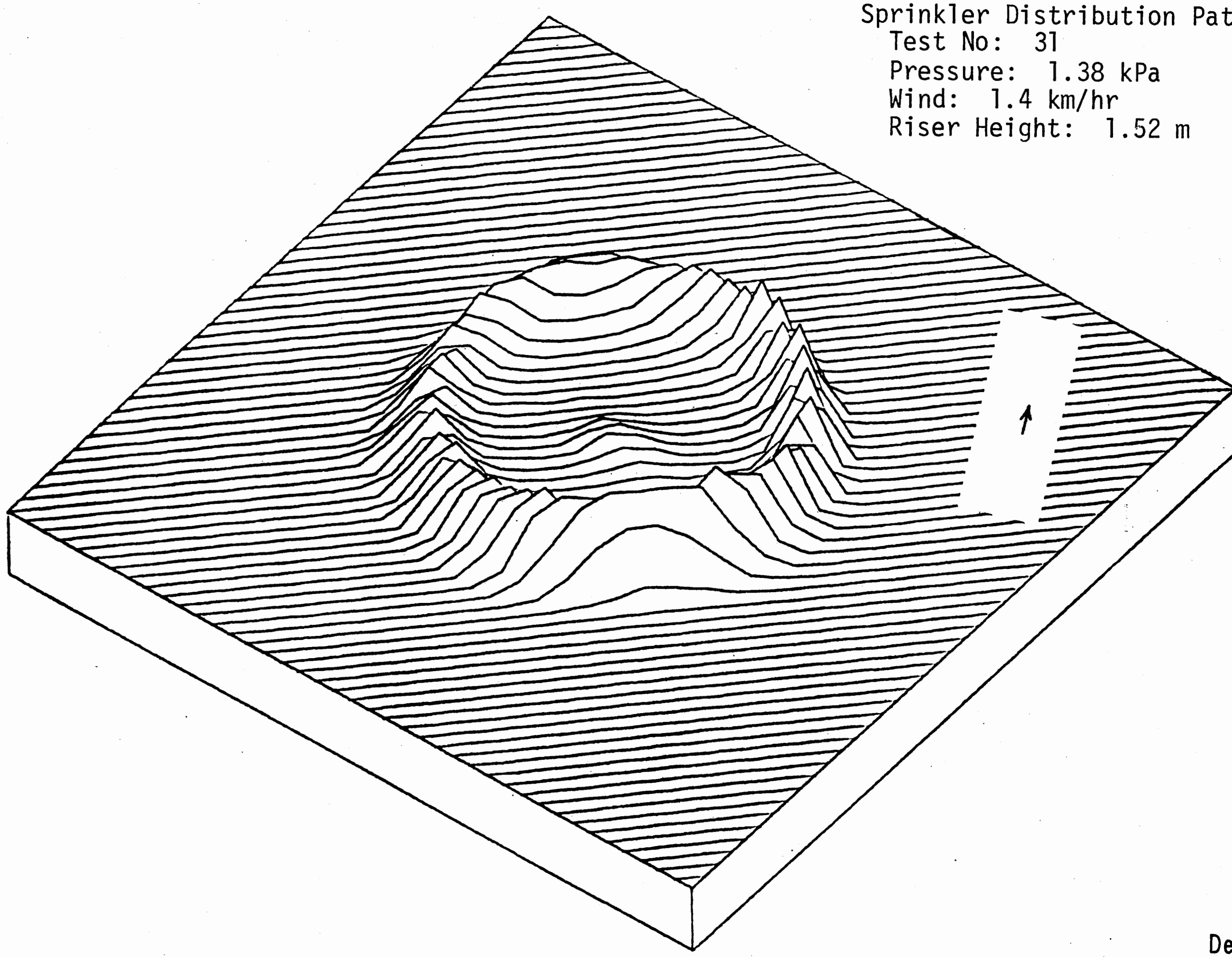
Sprinkler Distribution Pattern For:
Test No: 30
Pressure: 276 kPa
Wind: 3.7 km/hr
Riser Height: 1.52 m

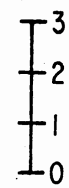



Sprinkler Distribution Pattern For:
Test No: 23
Pressure: 276 kPa
Wind: 4.5 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm

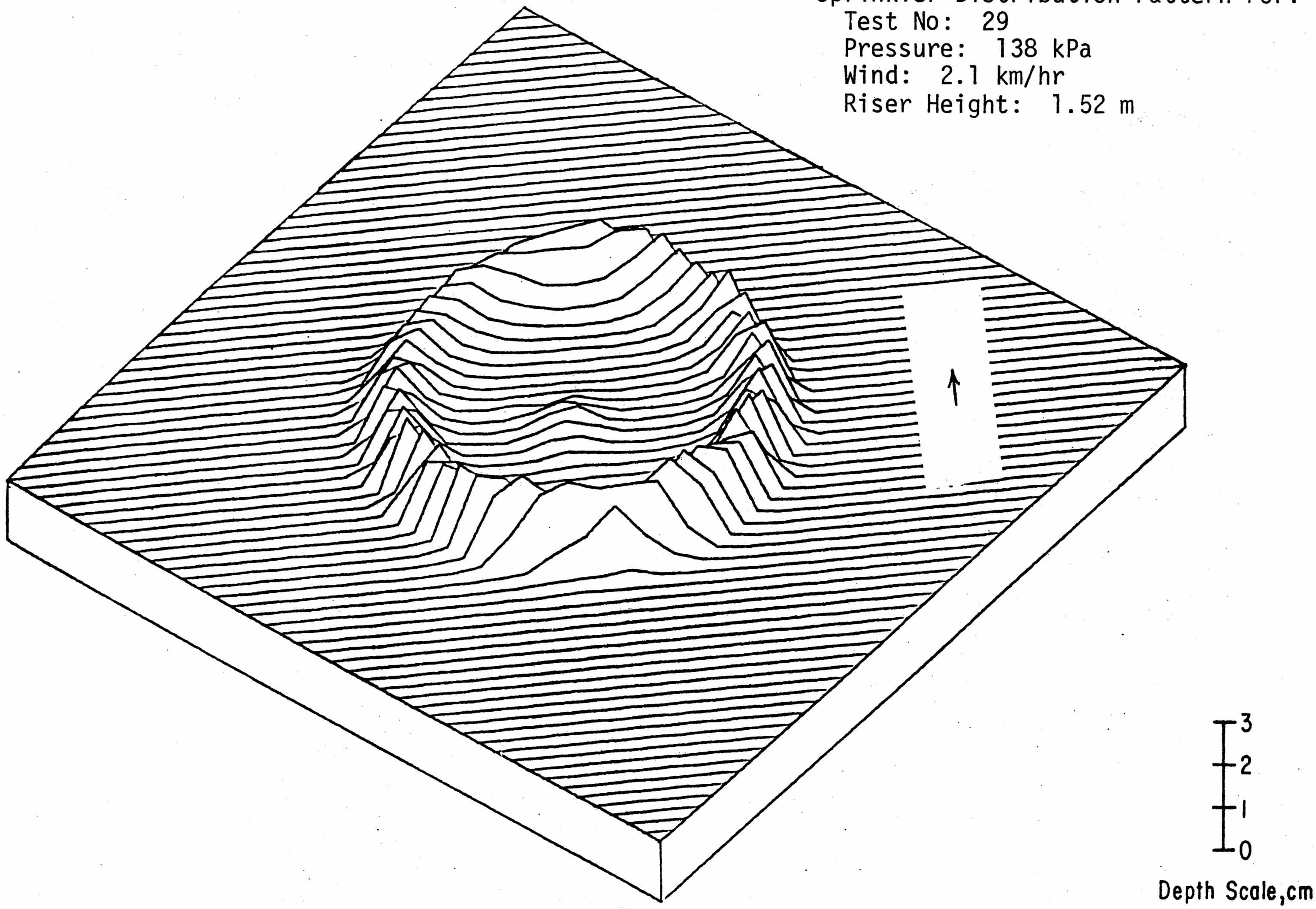

Sprinkler Distribution Pattern For:
Test No: 22
Pressure: 276 kPa
Wind: 0.10 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm

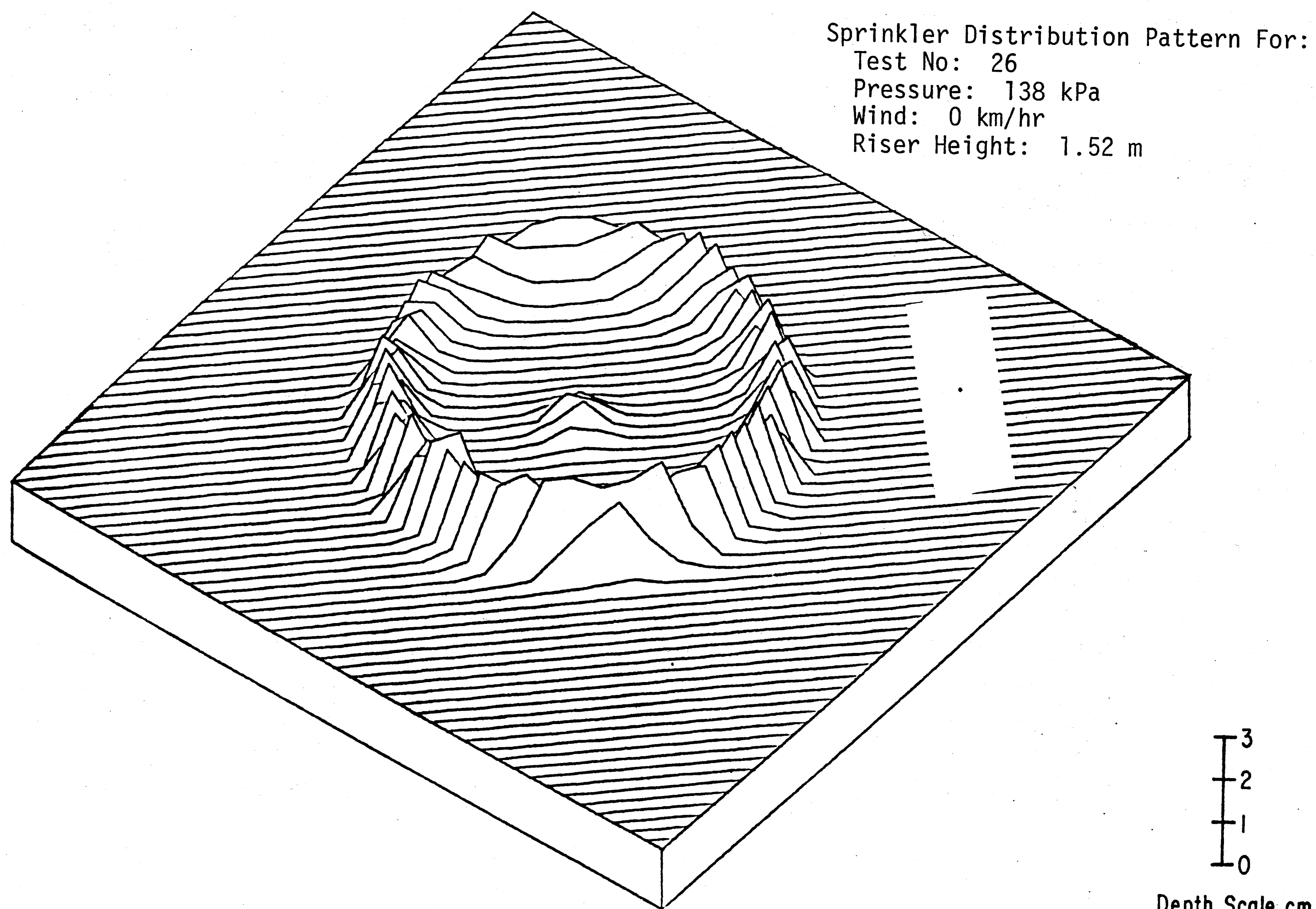
Sprinkler Distribution Pattern For:
Test No: 31
Pressure: 1.38 kPa
Wind: 1.4 km/hr
Riser Height: 1.52 m

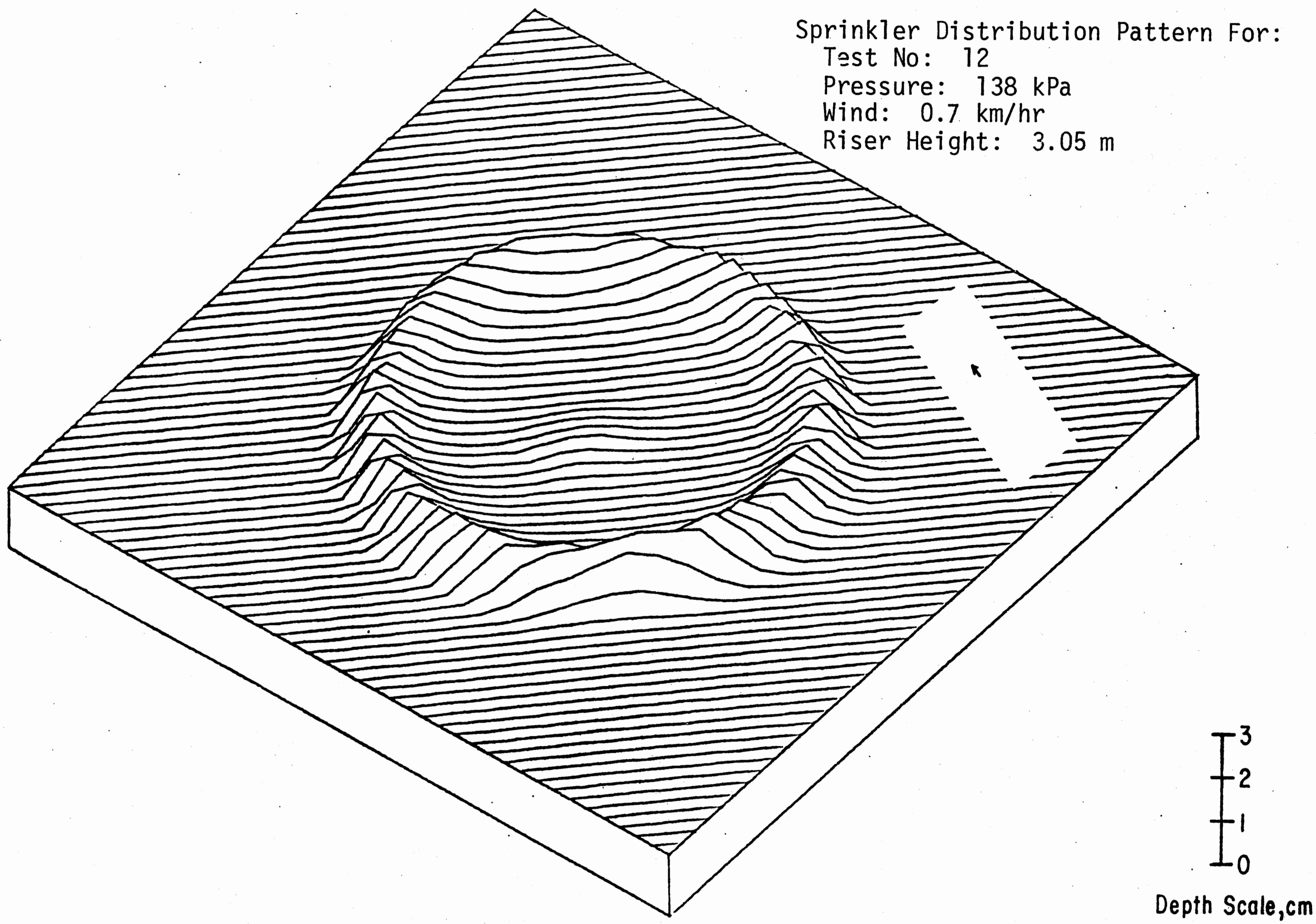




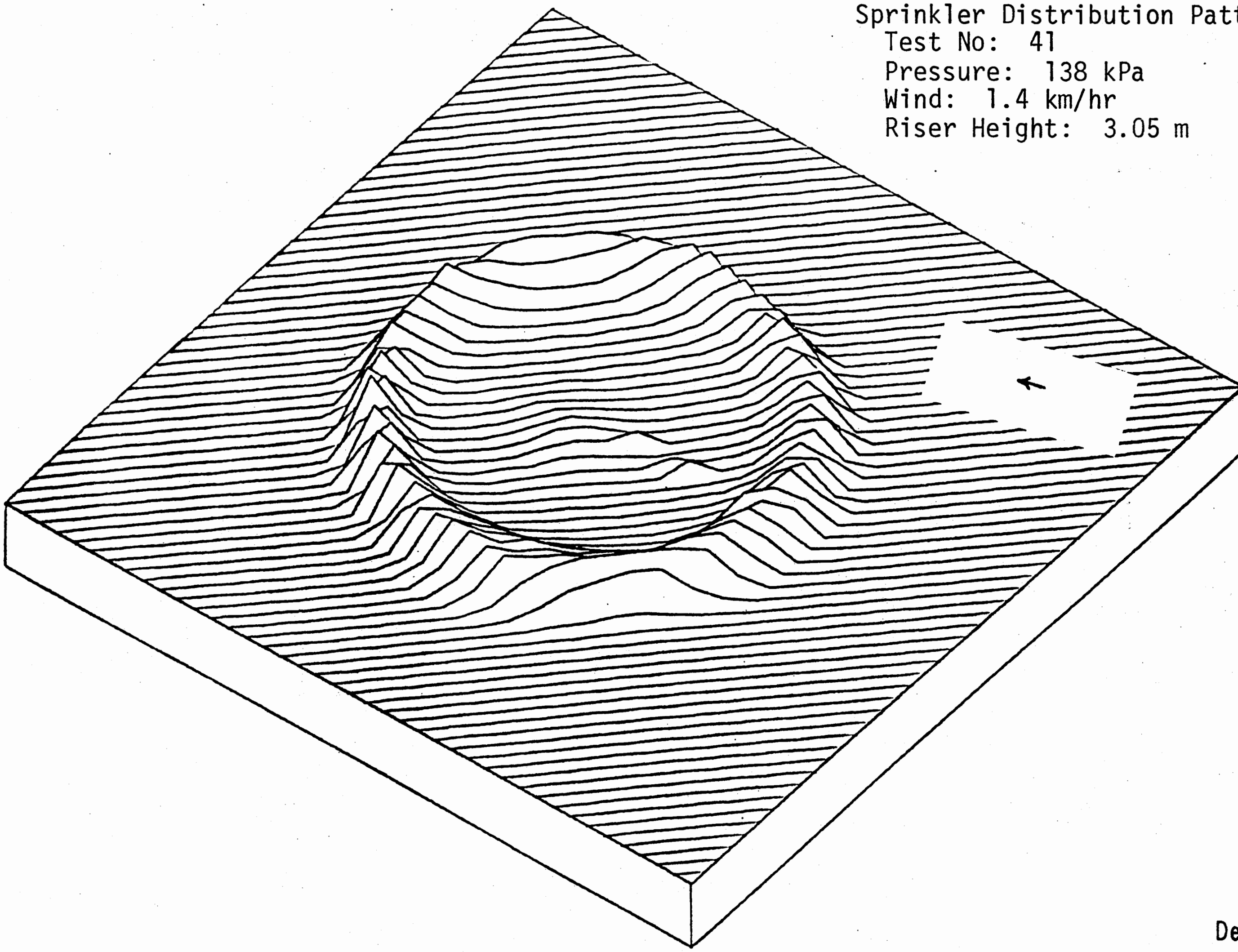
Sprinkler Distribution Pattern For:
Test No: 29
Pressure: 138 kPa
Wind: 2.1 km/hr
Riser Height: 1.52 m

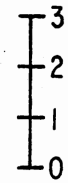



Sprinkler Distribution Pattern For:
Test No: 26
Pressure: 138 kPa
Wind: 0 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm

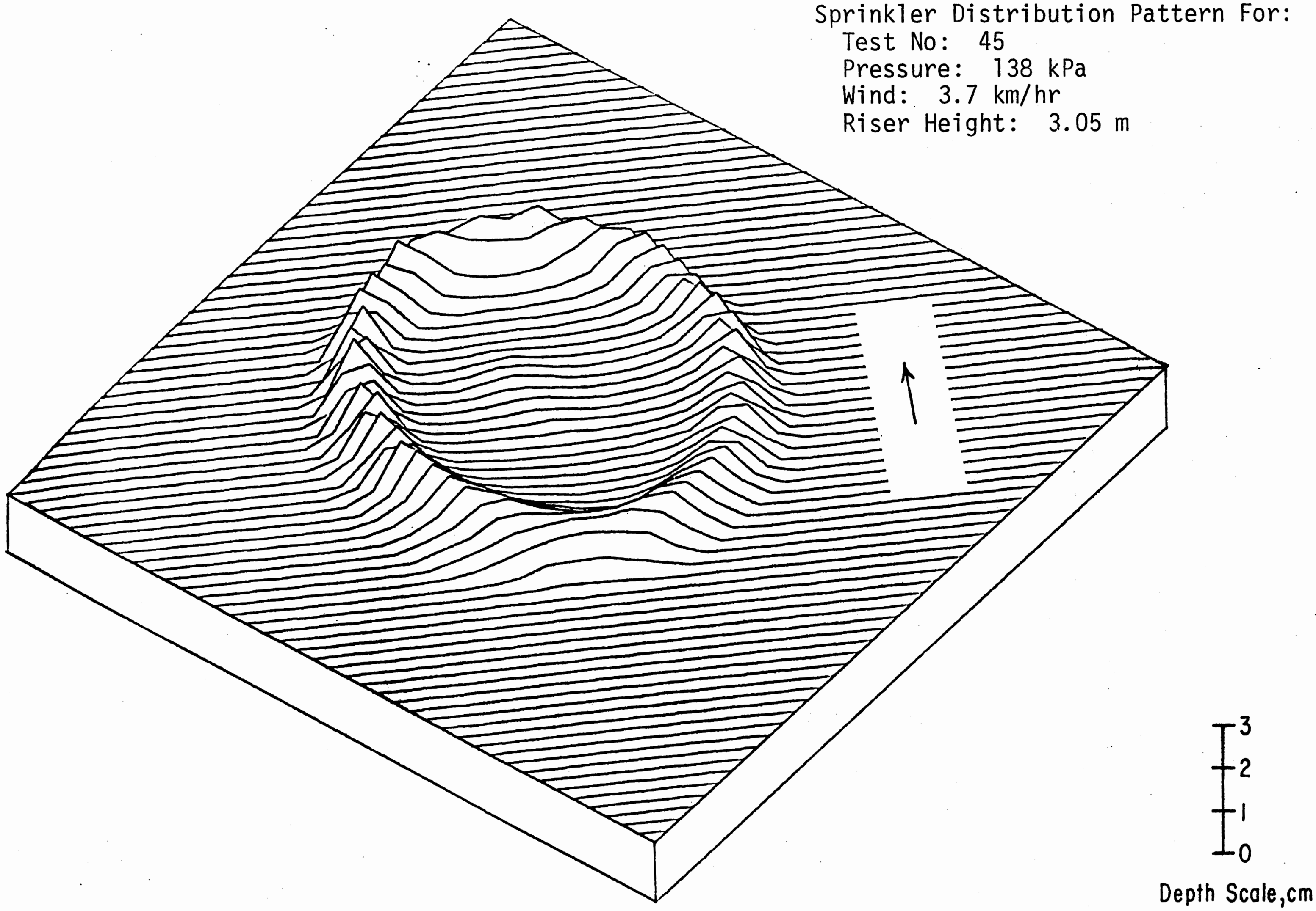

Sprinkler Distribution Pattern For:
Test No: 12
Pressure: 138 kPa
Wind: 0.7 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm

Sprinkler Distribution Pattern For:
Test No: 41
Pressure: 138 kPa
Wind: 1.4 km/hr
Riser Height: 3.05 m

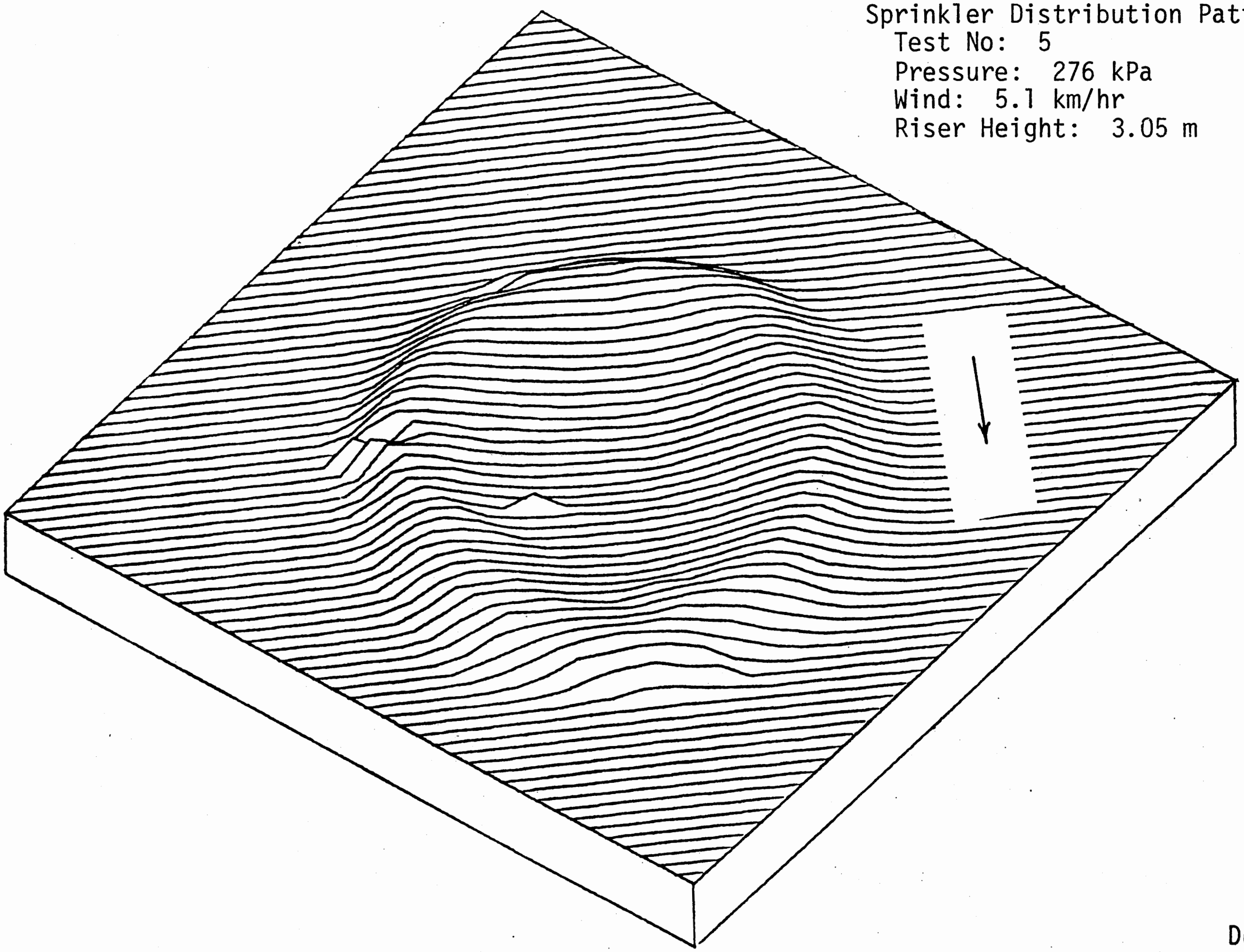


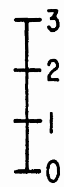


Sprinkler Distribution Pattern For:
Test No: 45
Pressure: 138 kPa
Wind: 3.7 km/hr
Riser Height: 3.05 m

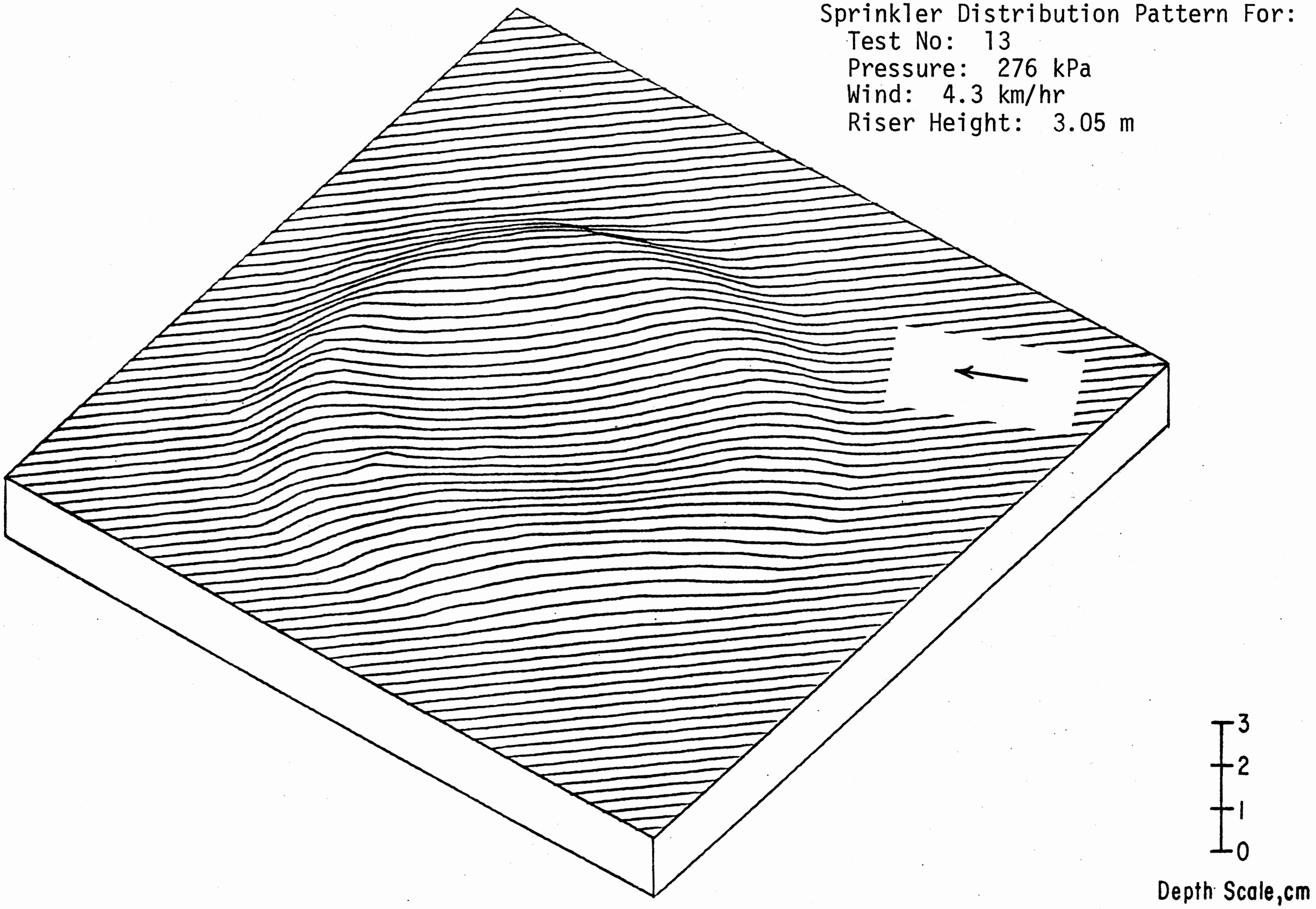


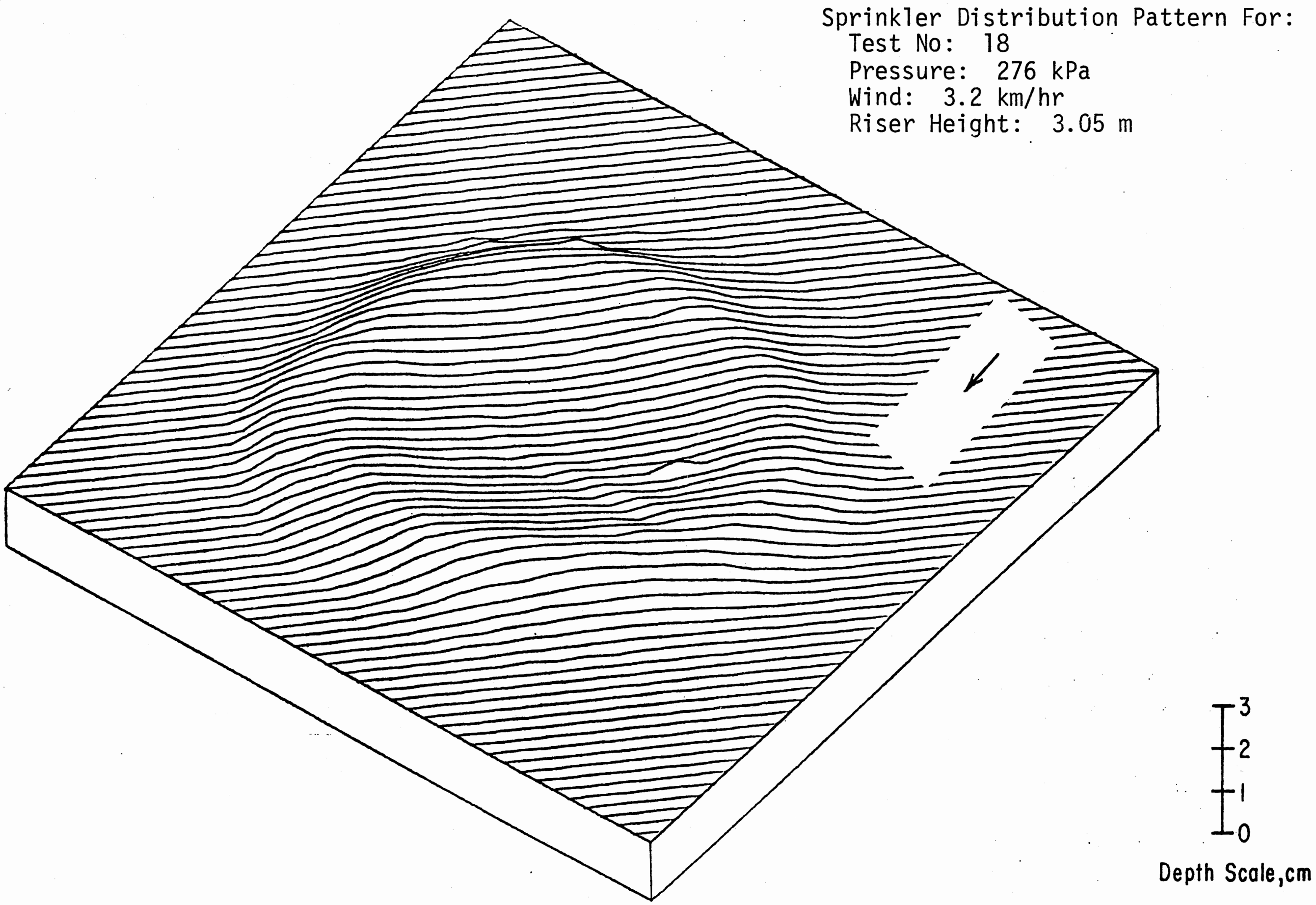
Sprinkler Distribution Pattern For:
Test No: 5
Pressure: 276 kPa
Wind: 5.1 km/hr
Riser Height: 3.05 m



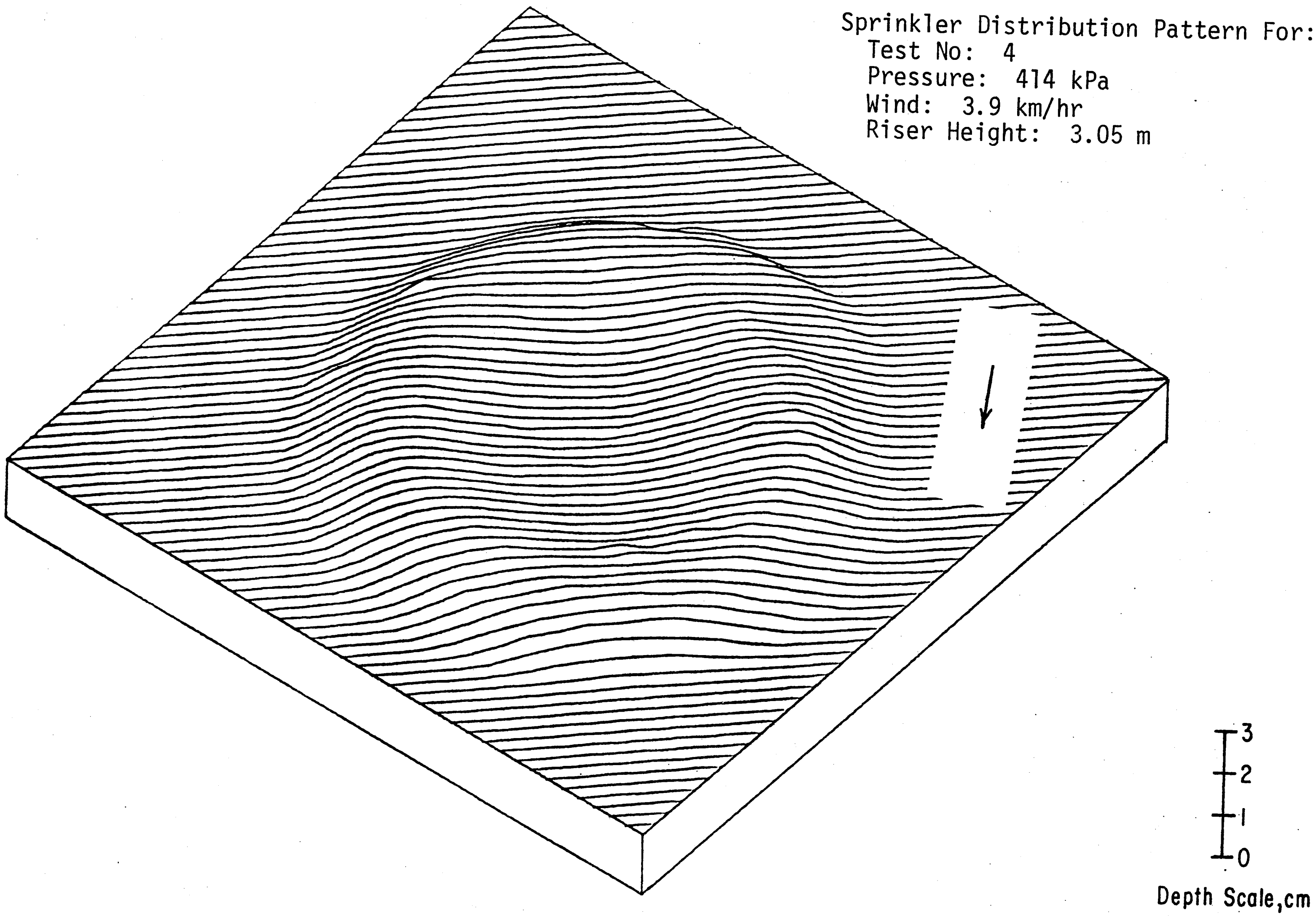


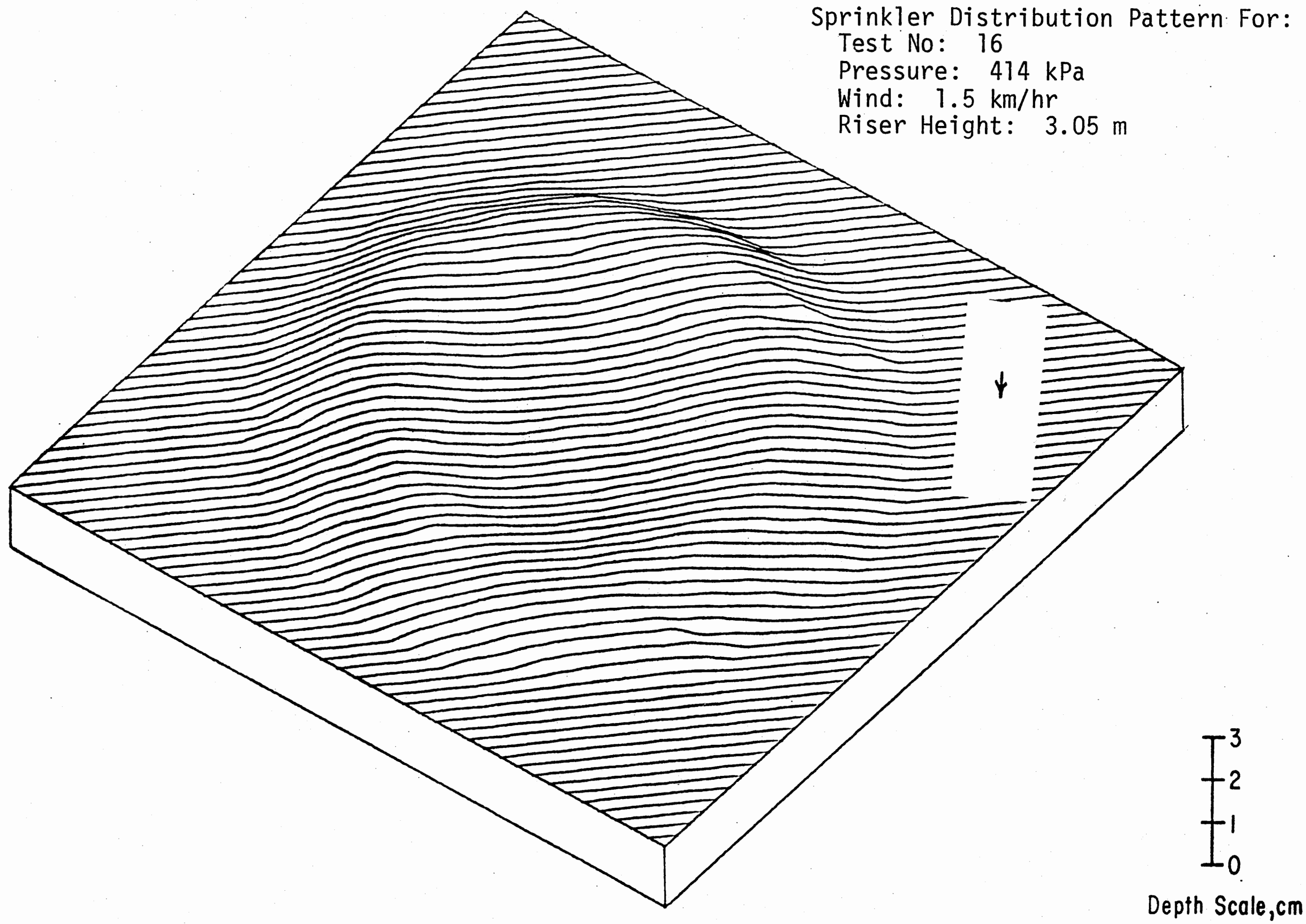
Sprinkler Distribution Pattern For:
Test No: 13
Pressure: 276 kPa
Wind: 4.3 km/hr
Riser Height: 3.05 m



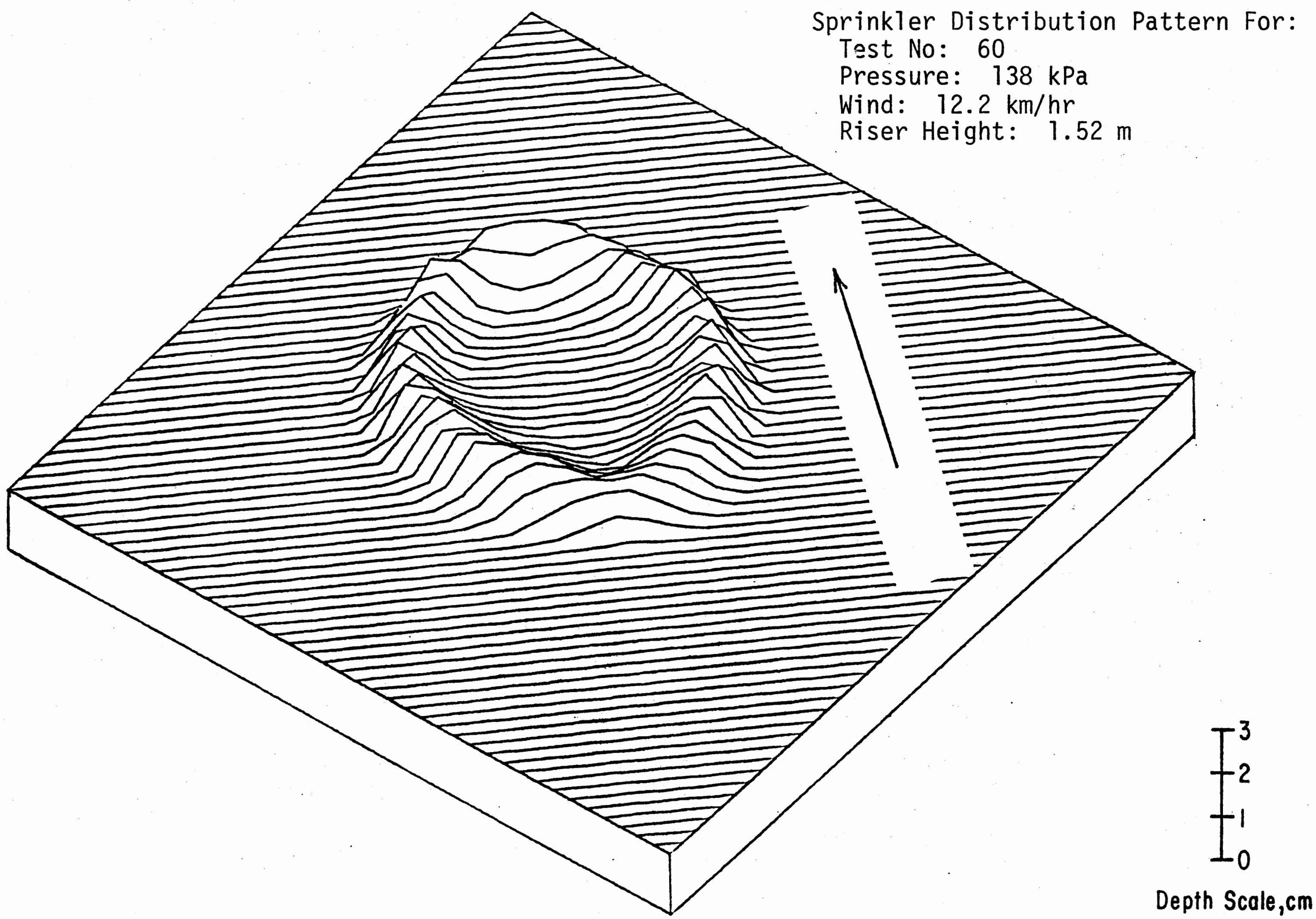


Sprinkler Distribution Pattern For:
Test No: 18
Pressure: 276 kPa
Wind: 3.2 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm

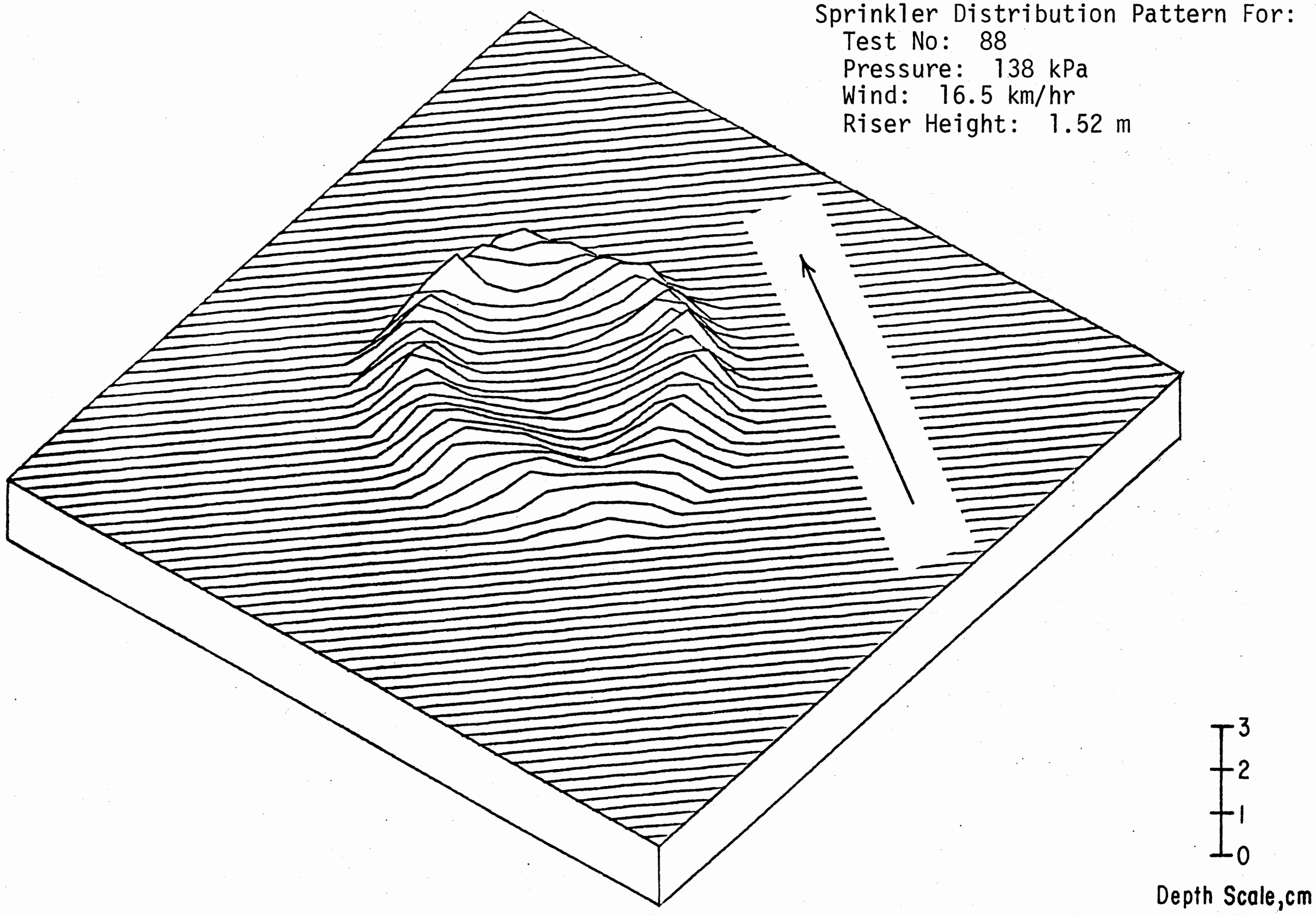

Sprinkler Distribution Pattern For:
Test No: 4
Pressure: 414 kPa
Wind: 3.9 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm

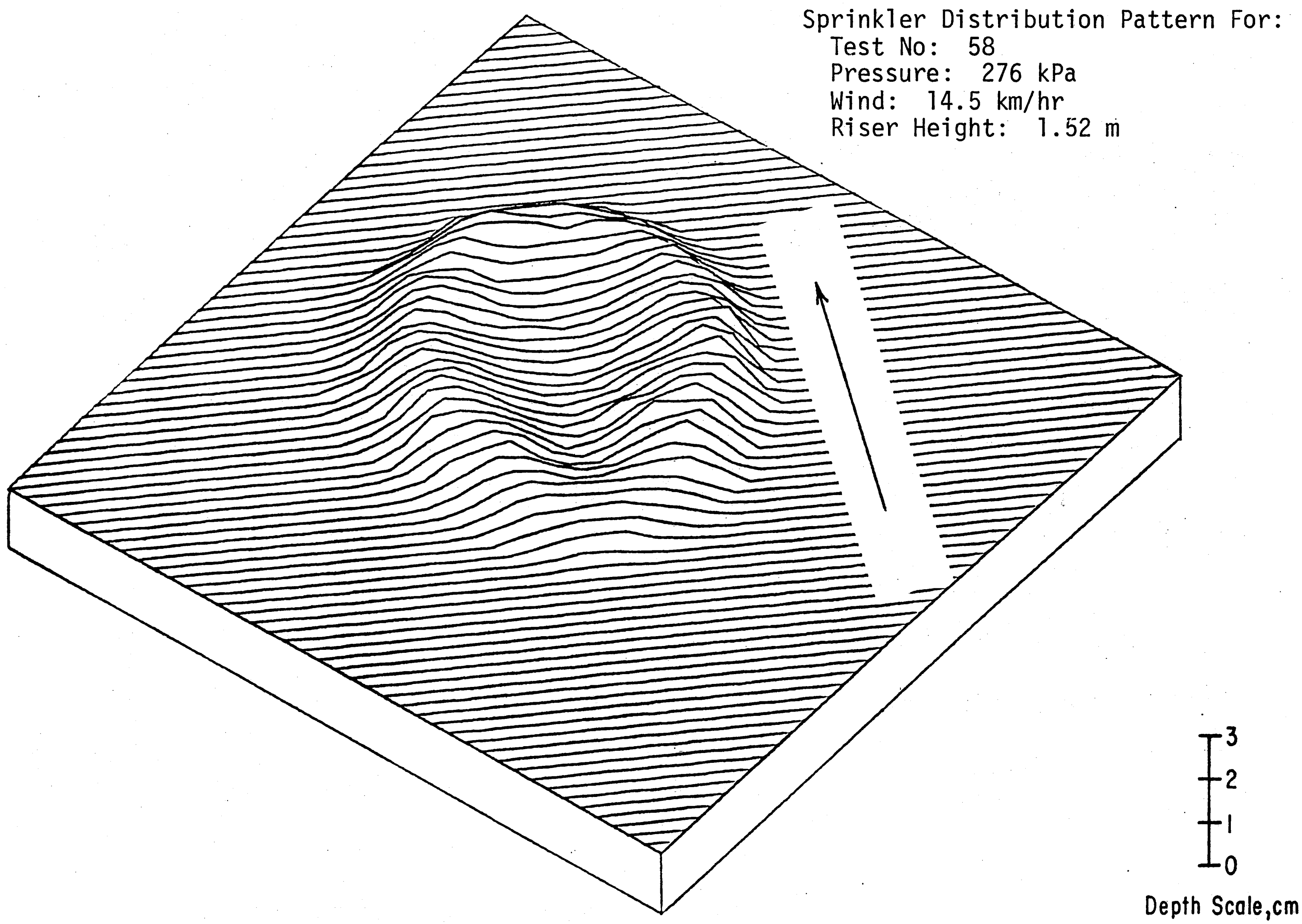


Sprinkler Distribution Pattern For:
Test No: 16
Pressure: 414 kPa
Wind: 1.5 km/hr
Riser Height: 3.05 m

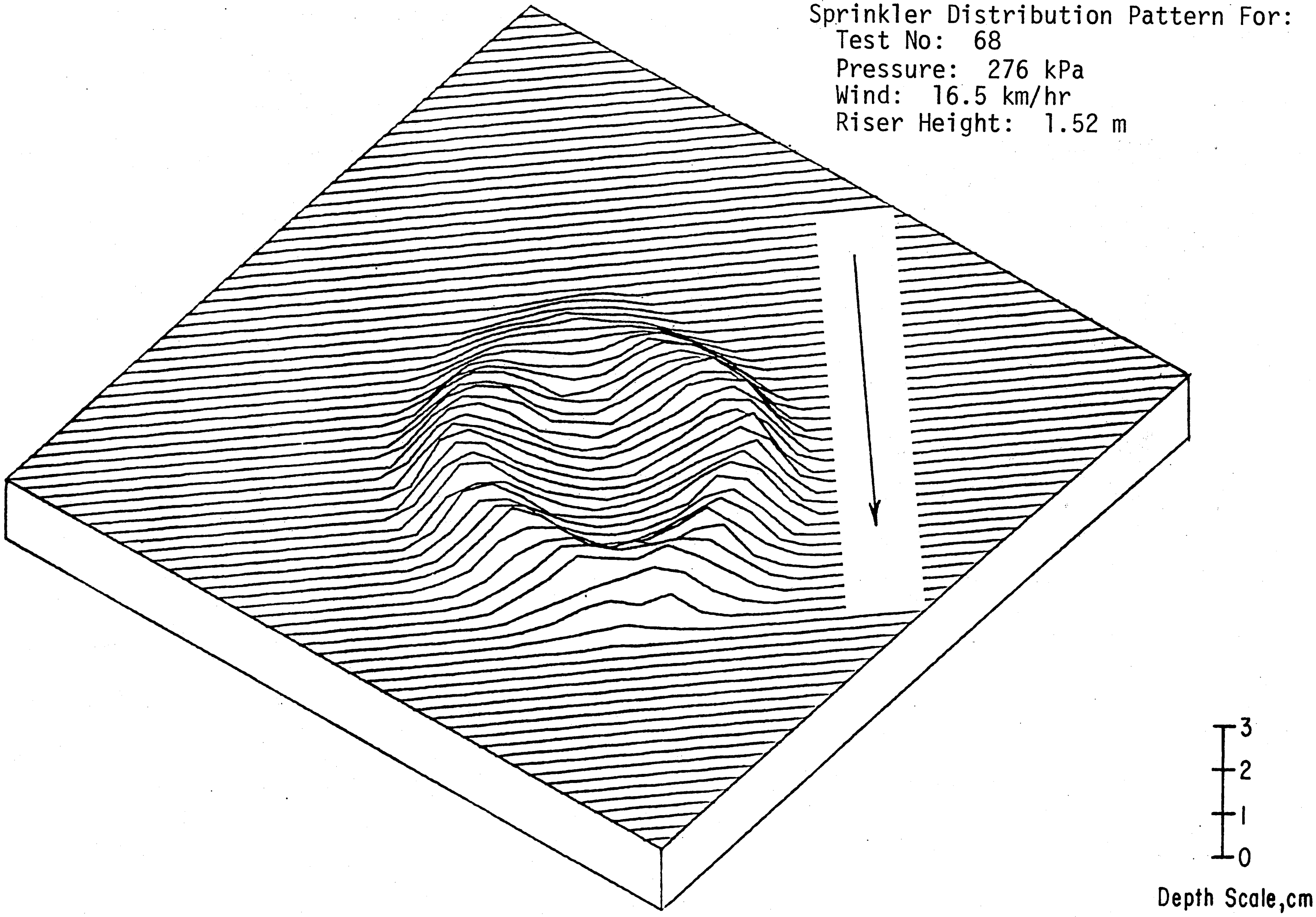

Sprinkler Distribution Pattern For:
Test No: 60
Pressure: 138 kPa
Wind: 12.2 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm

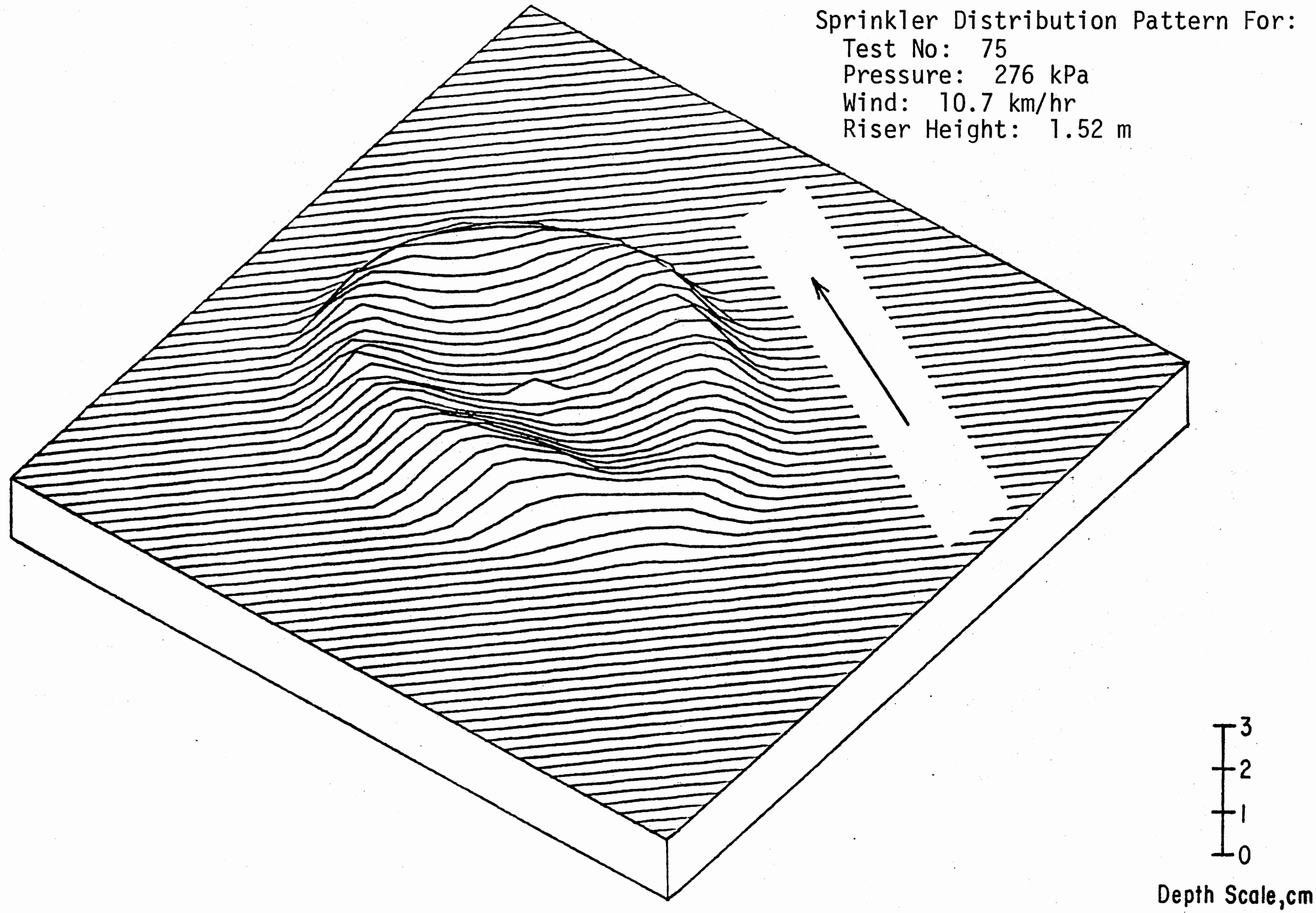
Sprinkler Distribution Pattern For:
Test No: 88
Pressure: 138 kPa
Wind: 16.5 km/hr
Riser Height: 1.52 m



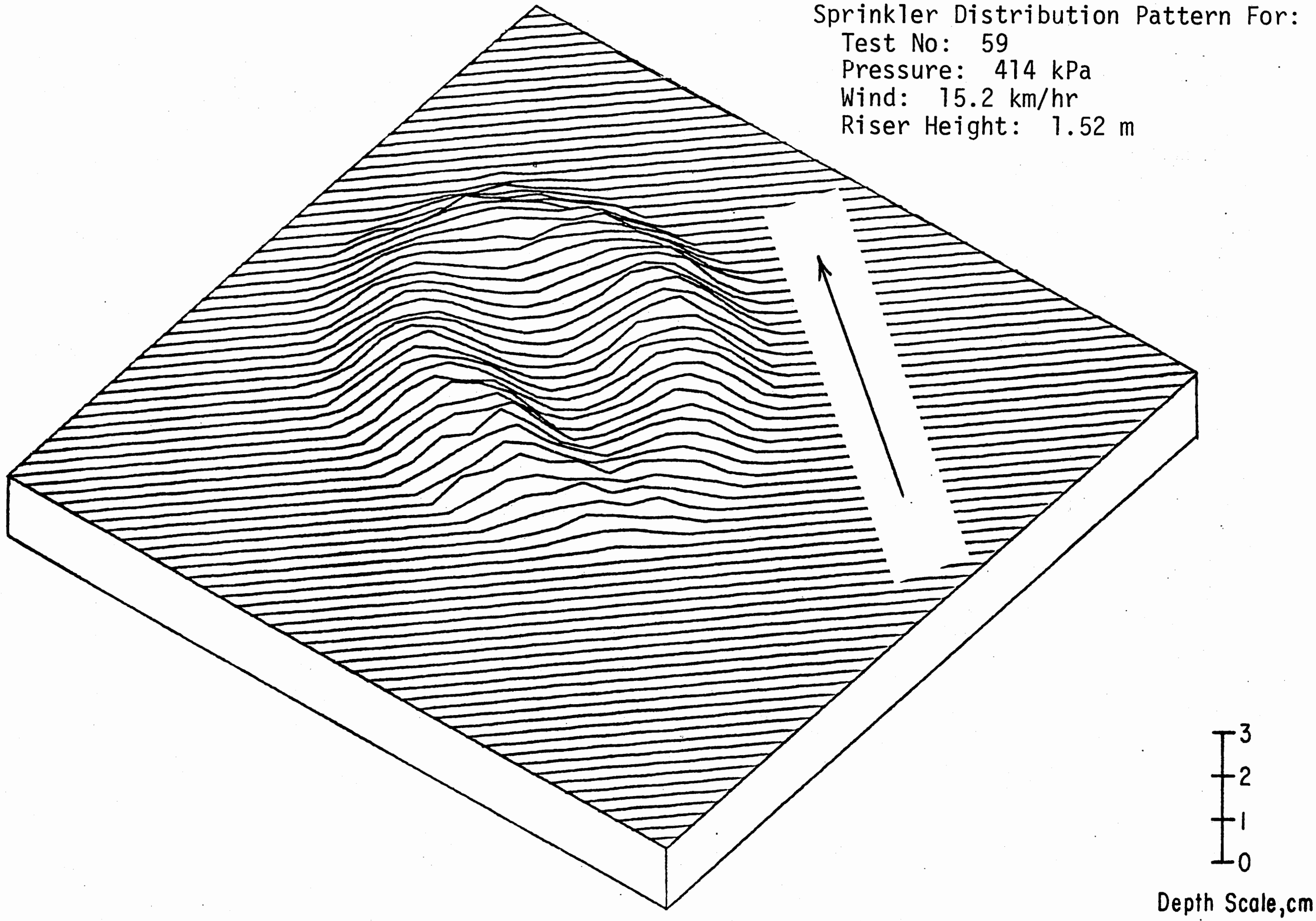

Sprinkler Distribution Pattern For:
Test No: 58
Pressure: 276 kPa
Wind: 14.5 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm

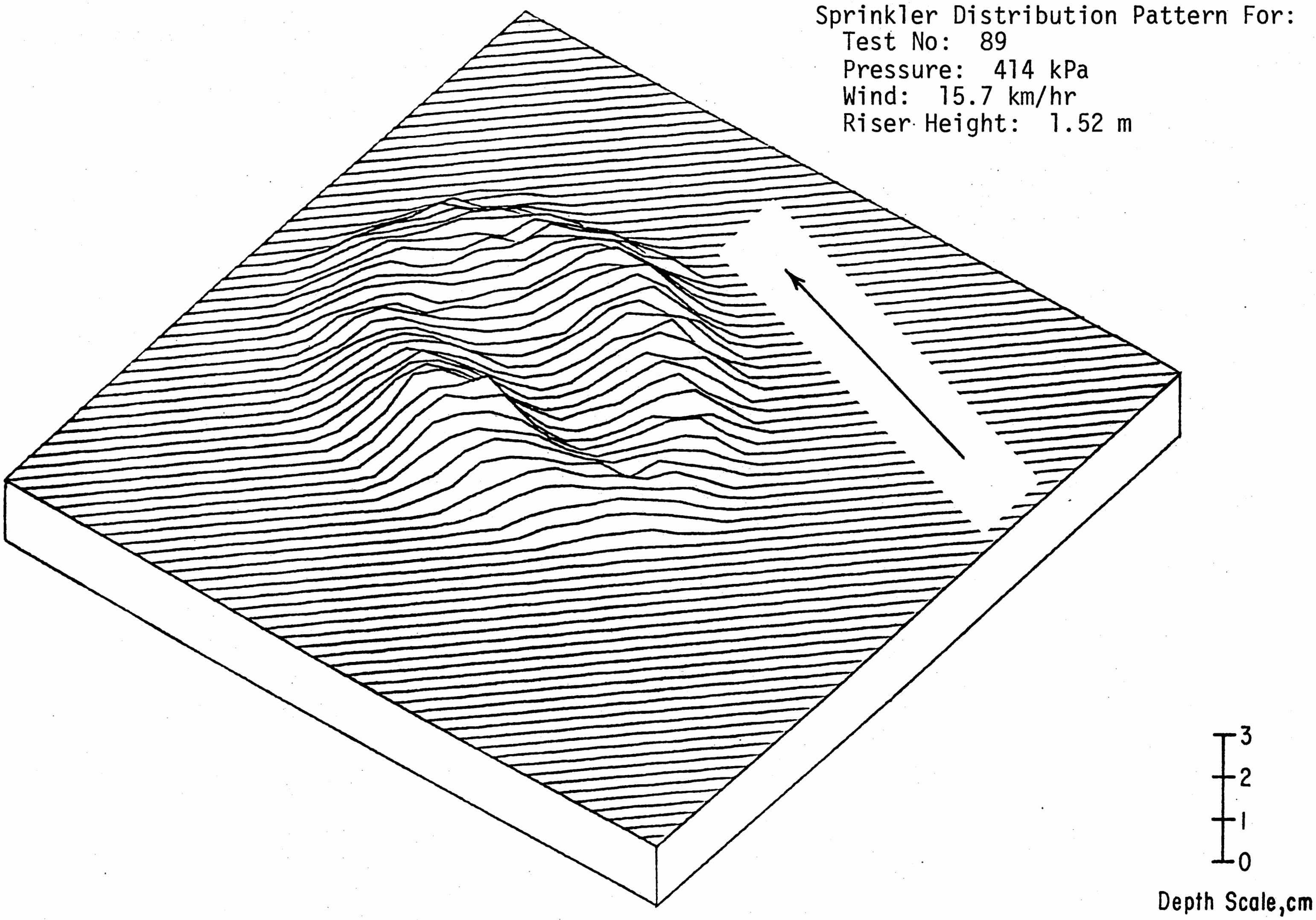
Sprinkler Distribution Pattern For:
Test No: 68
Pressure: 276 kPa
Wind: 16.5 km/hr
Riser Height: 1.52 m

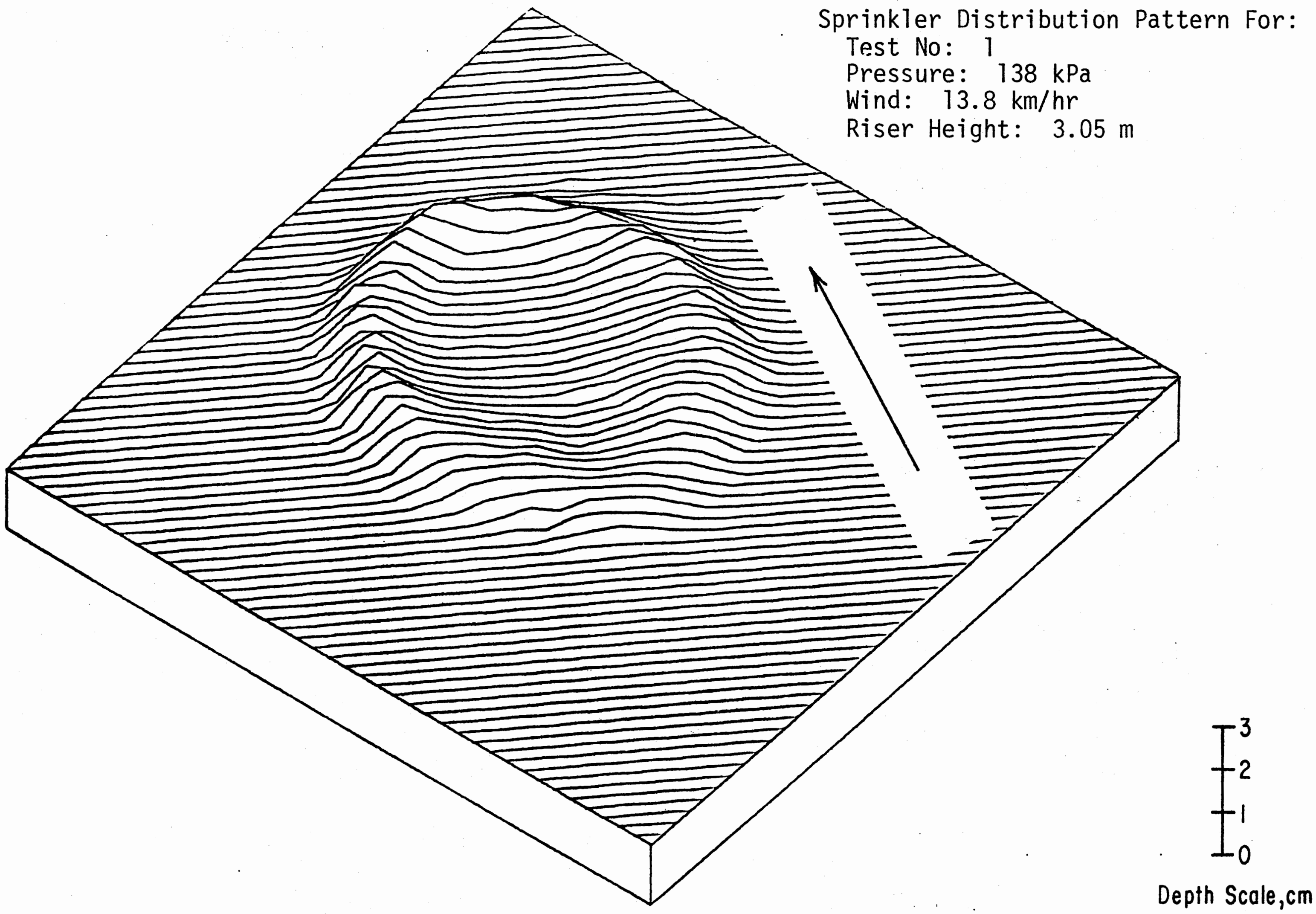


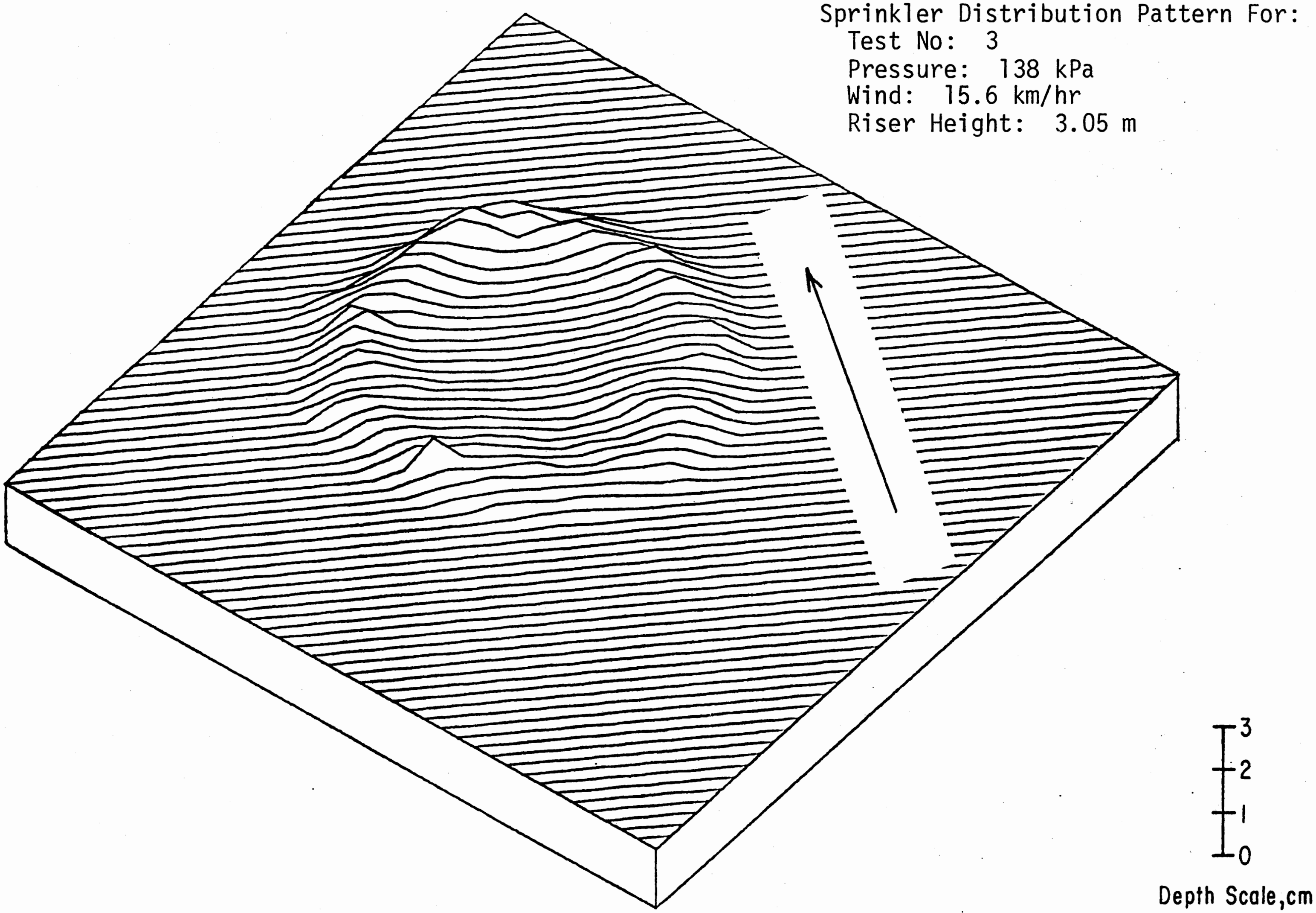


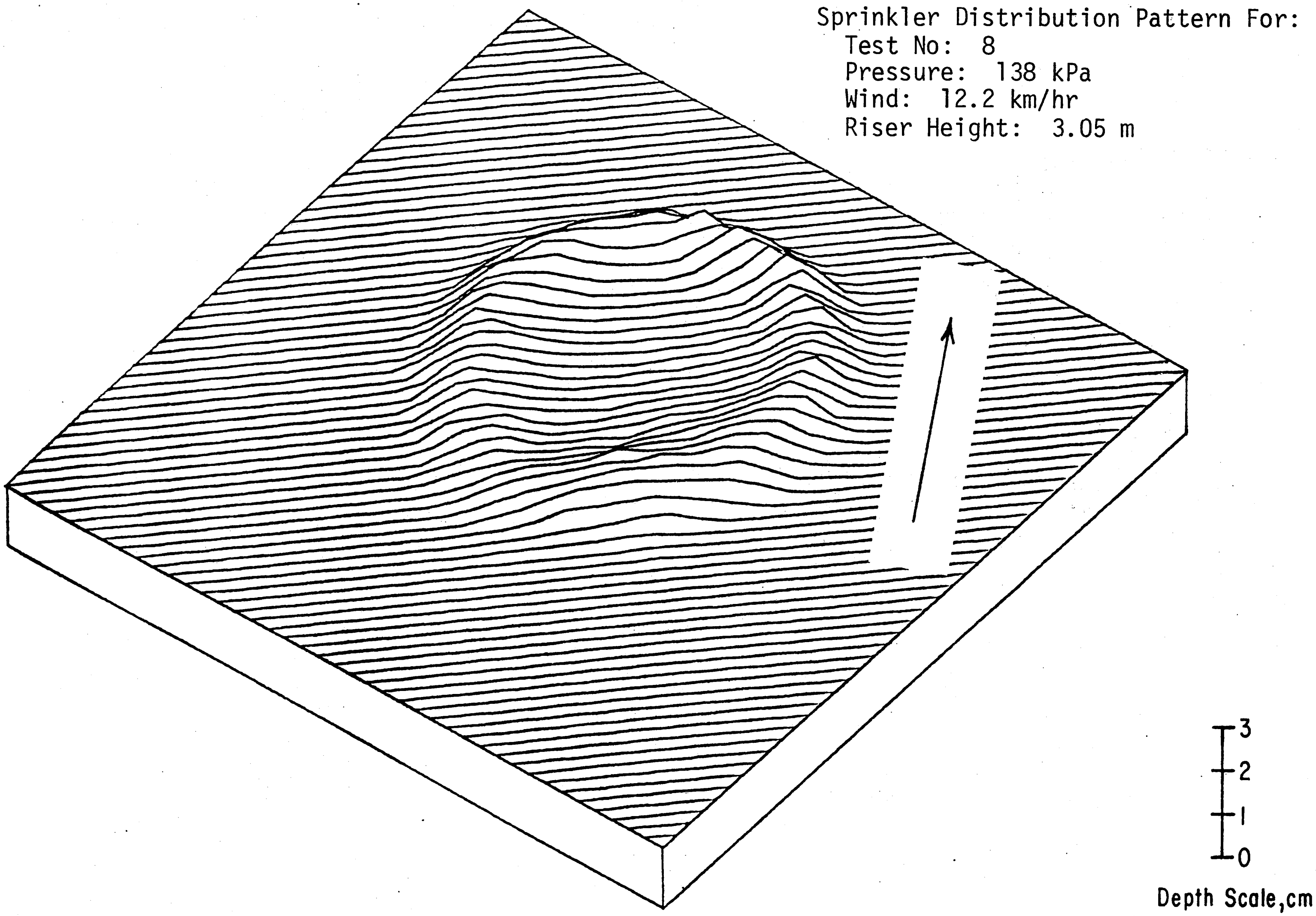
Sprinkler Distribution Pattern For:
Test No: 75
Pressure: 276 kPa
Wind: 10.7 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm

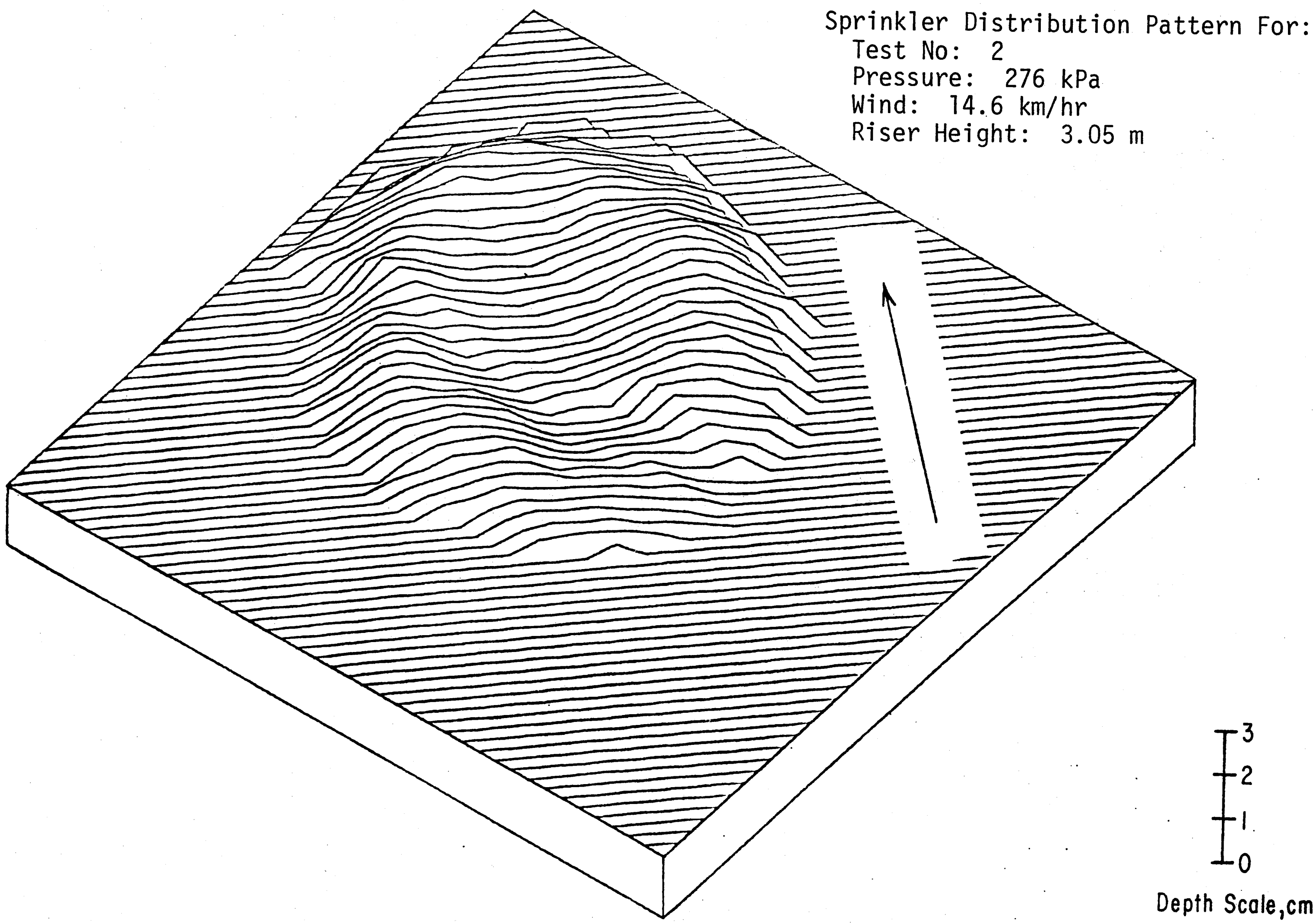

Sprinkler Distribution Pattern For:
Test No: 59
Pressure: 414 kPa
Wind: 15.2 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm

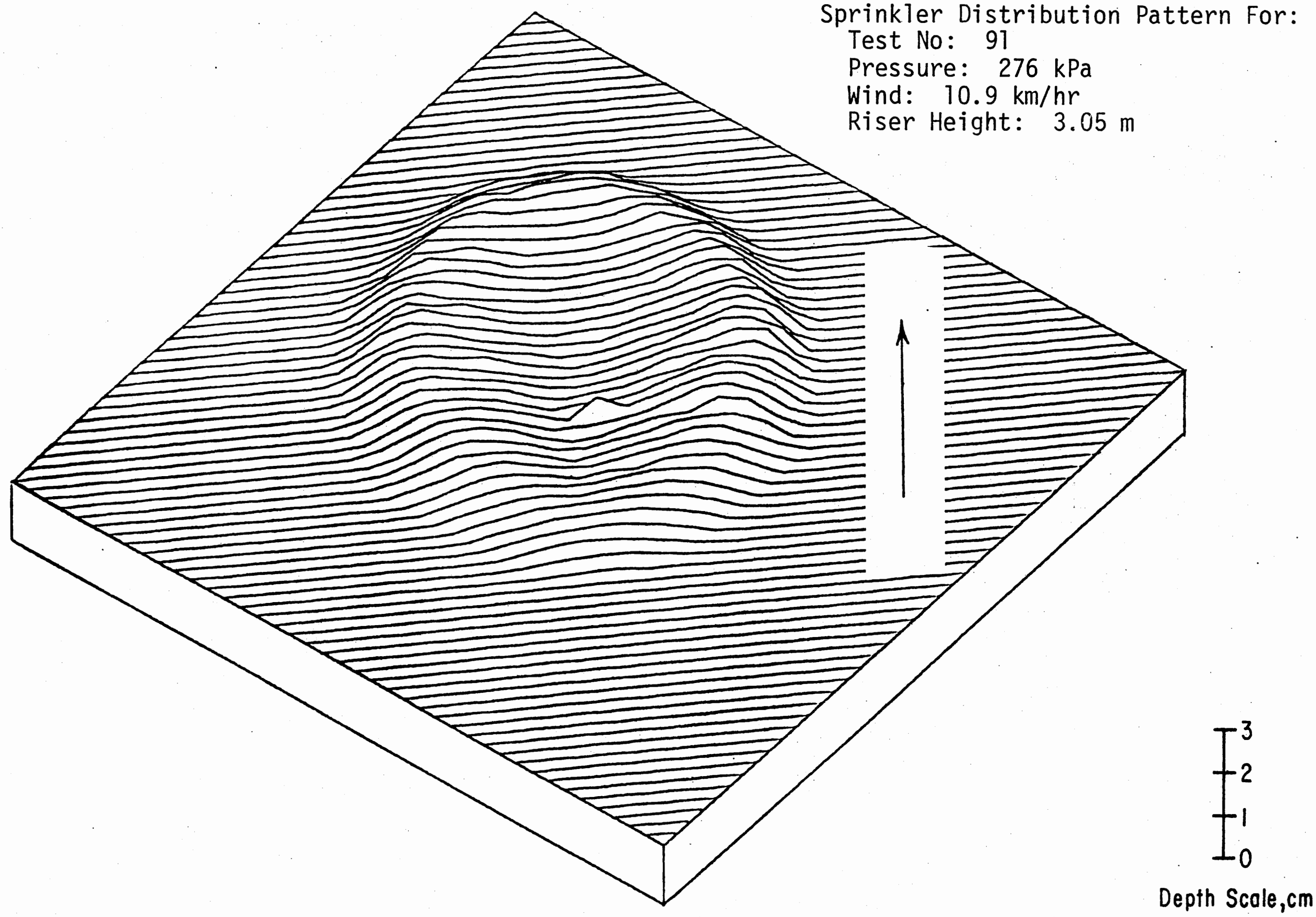

Sprinkler Distribution Pattern For:
Test No: 89
Pressure: 414 kPa
Wind: 15.7 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm


Sprinkler Distribution Pattern For:
Test No: 1
Pressure: 138 kPa
Wind: 13.8 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm

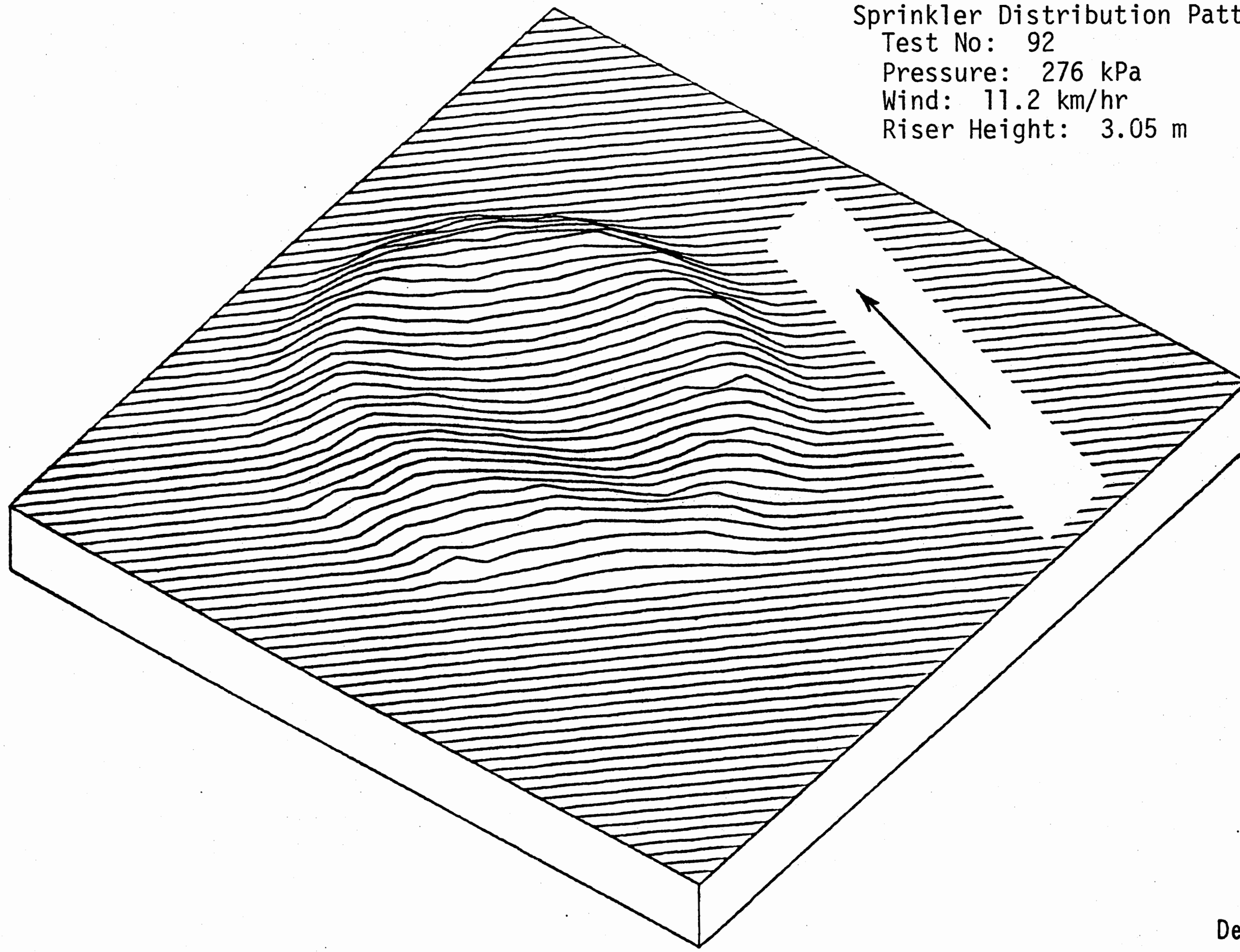

Sprinkler Distribution Pattern For:
Test No: 3
Pressure: 138 kPa
Wind: 15.6 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm

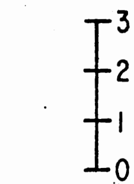

Sprinkler Distribution Pattern For:
Test No: 8
Pressure: 138 kPa
Wind: 12.2 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm


Sprinkler Distribution Pattern For:
Test No: 2
Pressure: 276 kPa
Wind: 14.6 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm

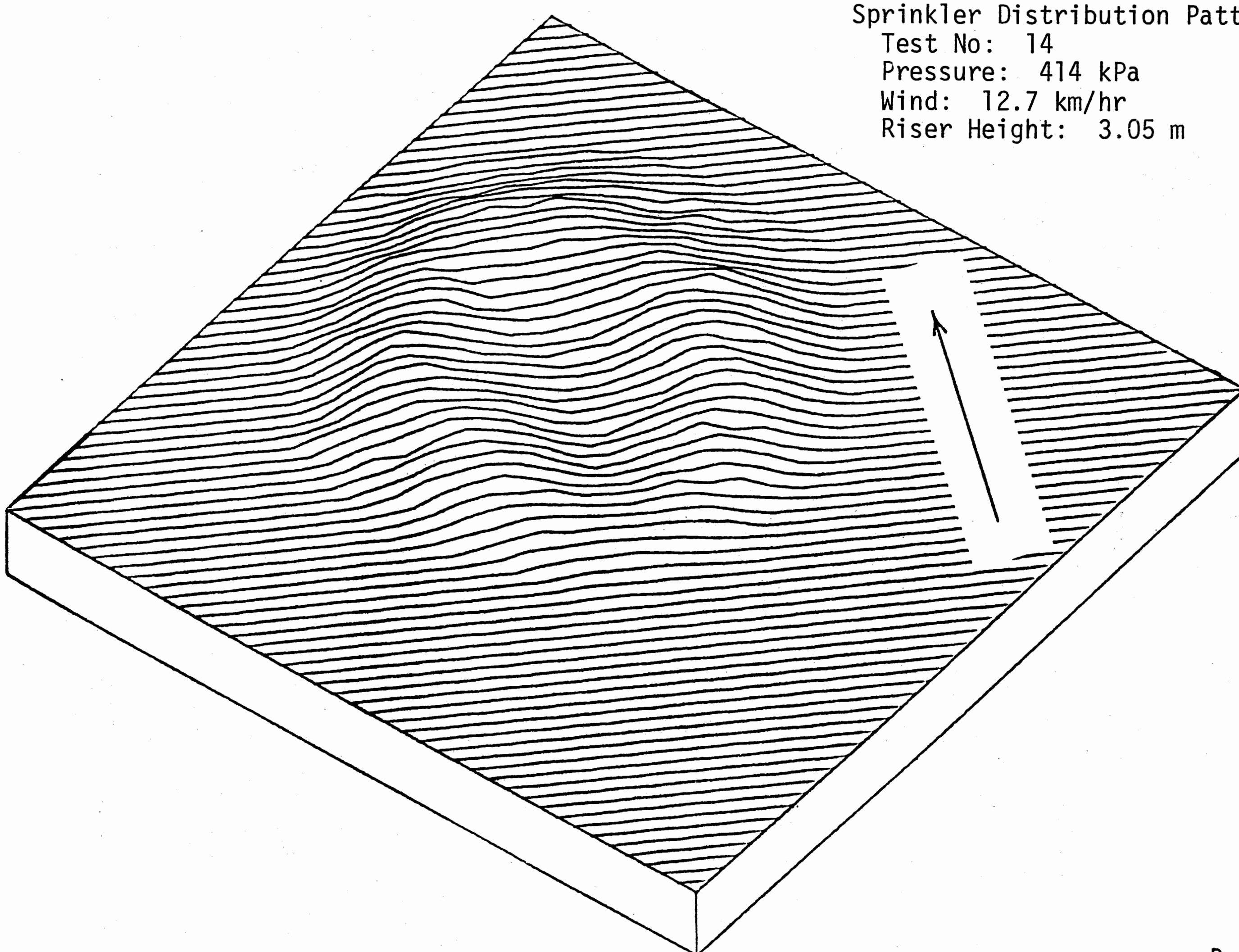

Sprinkler Distribution Pattern For:
Test No: 91
Pressure: 276 kPa
Wind: 10.9 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm

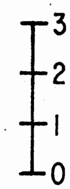
Sprinkler Distribution Pattern For:
Test No: 92
Pressure: 276 kPa
Wind: 11.2 km/hr
Riser Height: 3.05 m

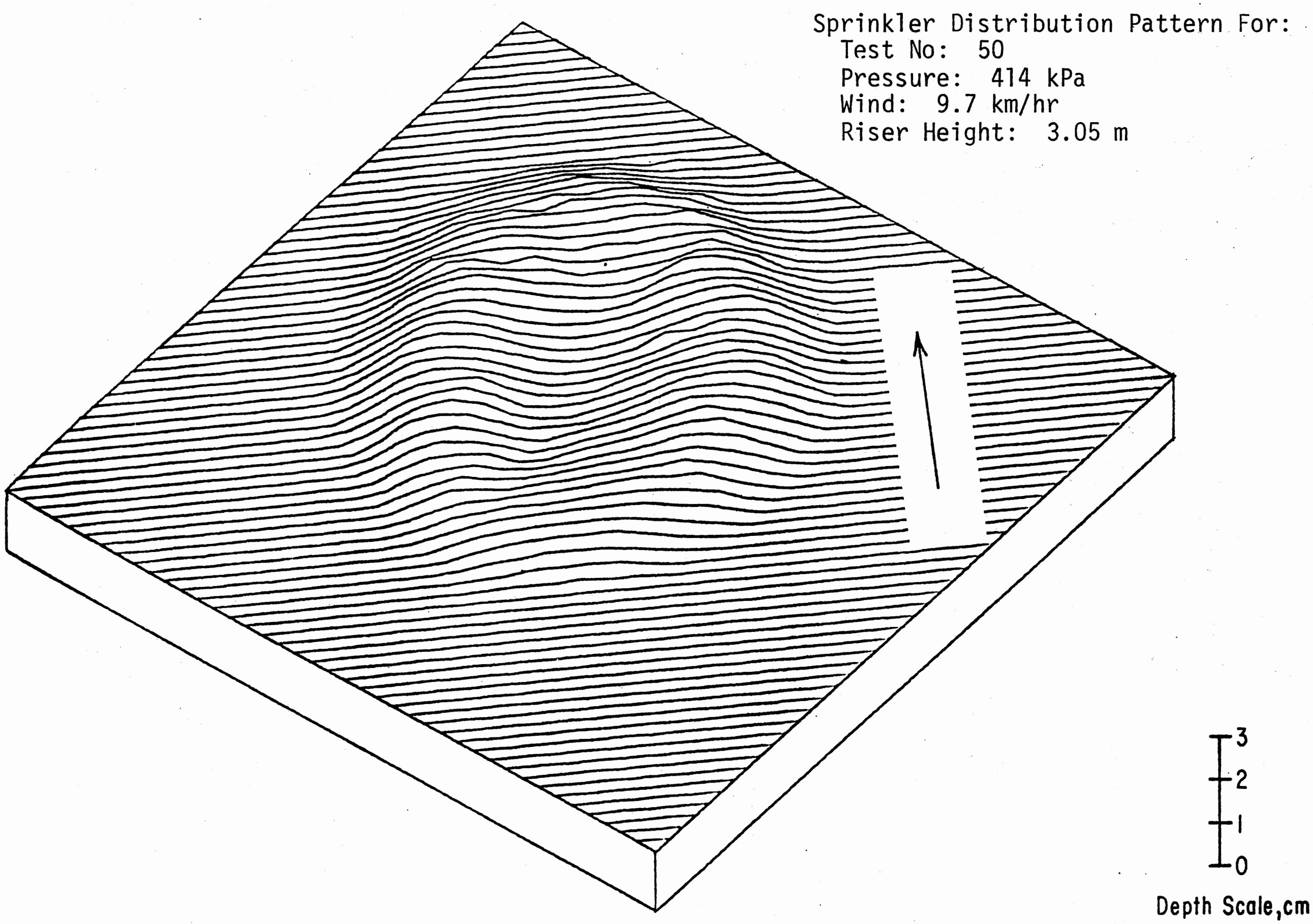




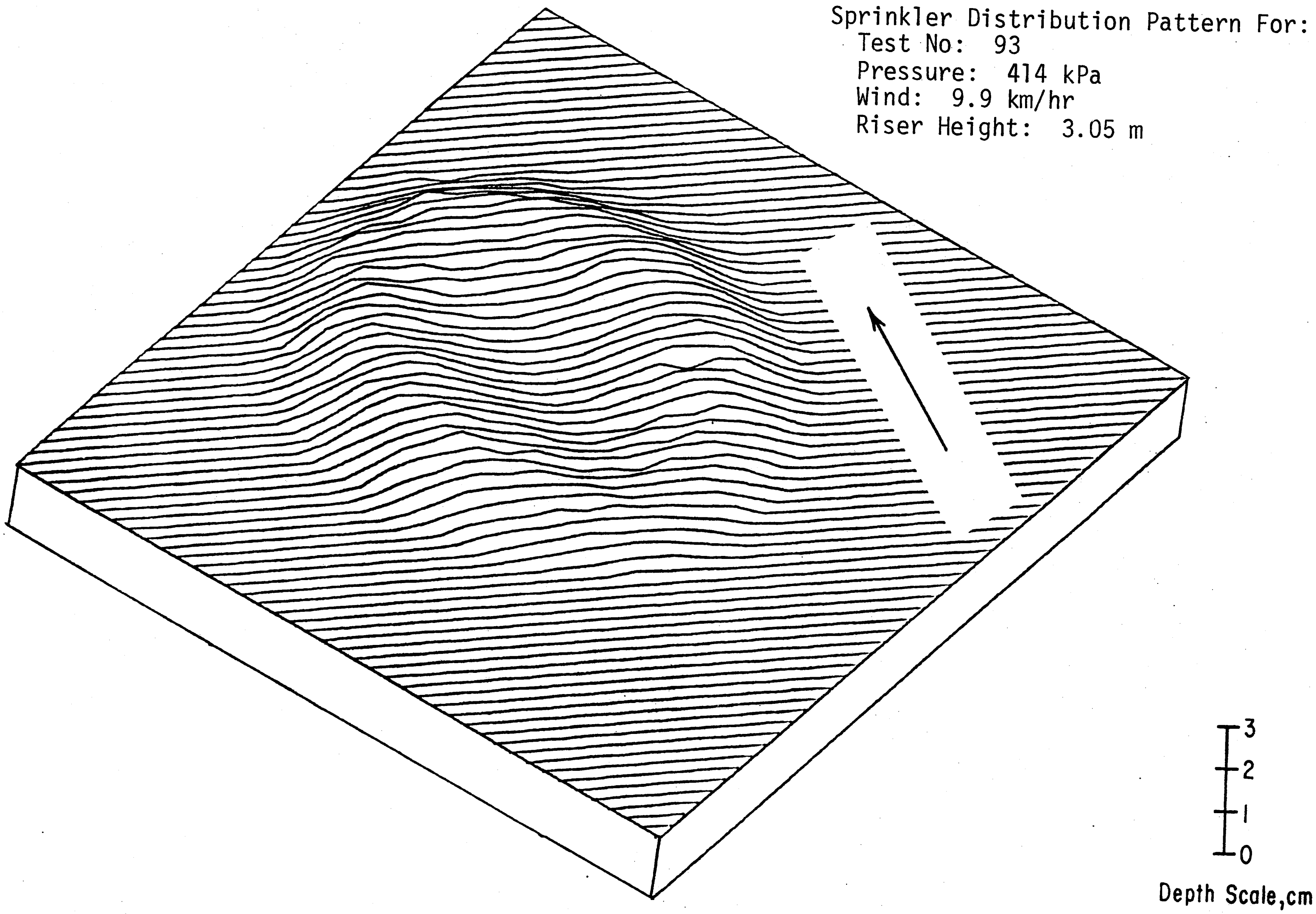
Sprinkler Distribution Pattern For:
Test No: 14
Pressure: 414 kPa
Wind: 12.7 km/hr
Riser Height: 3.05 m

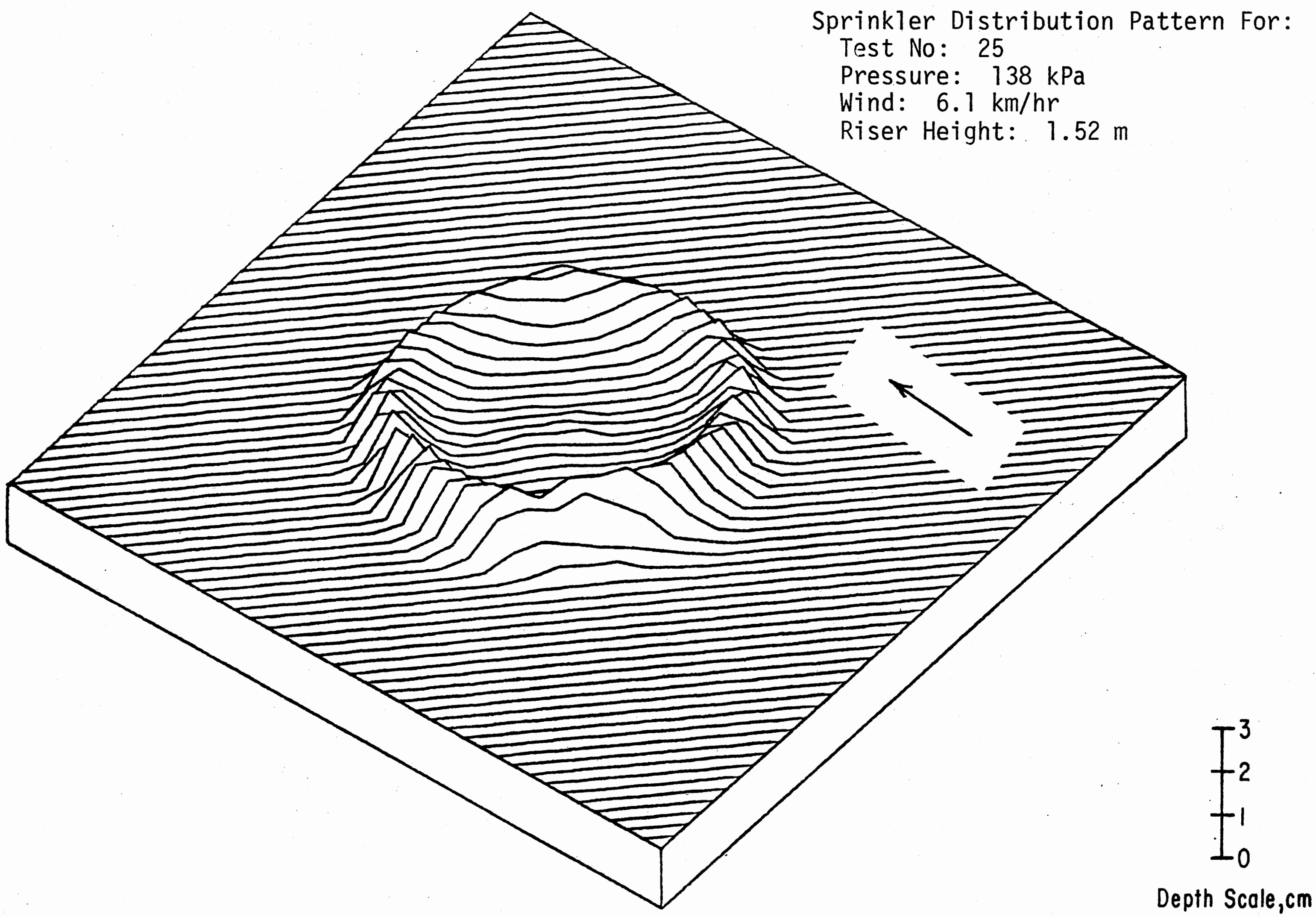


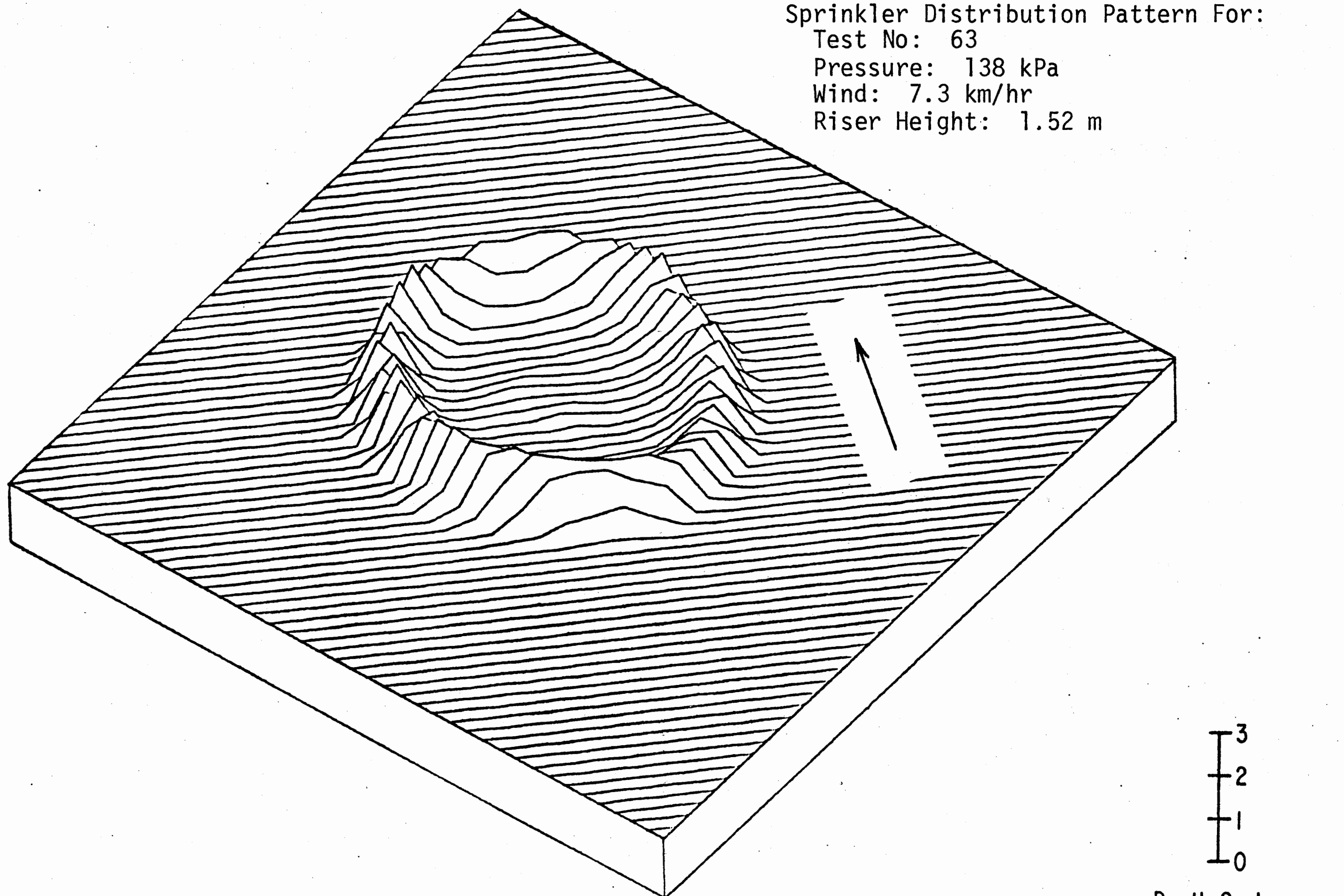




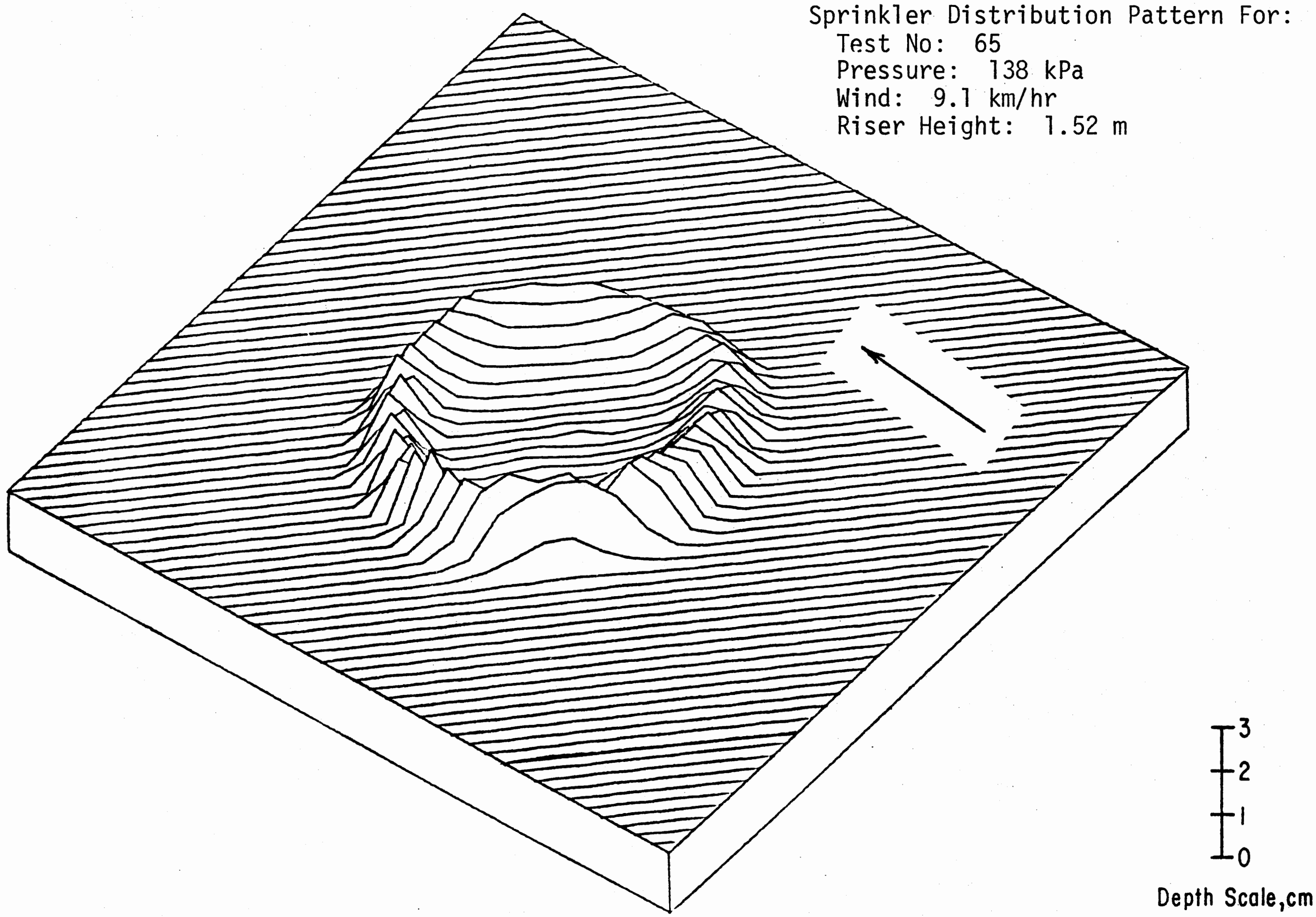
Sprinkler Distribution Pattern For:
Test No: 50
Pressure: 414 kPa
Wind: 9.7 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm

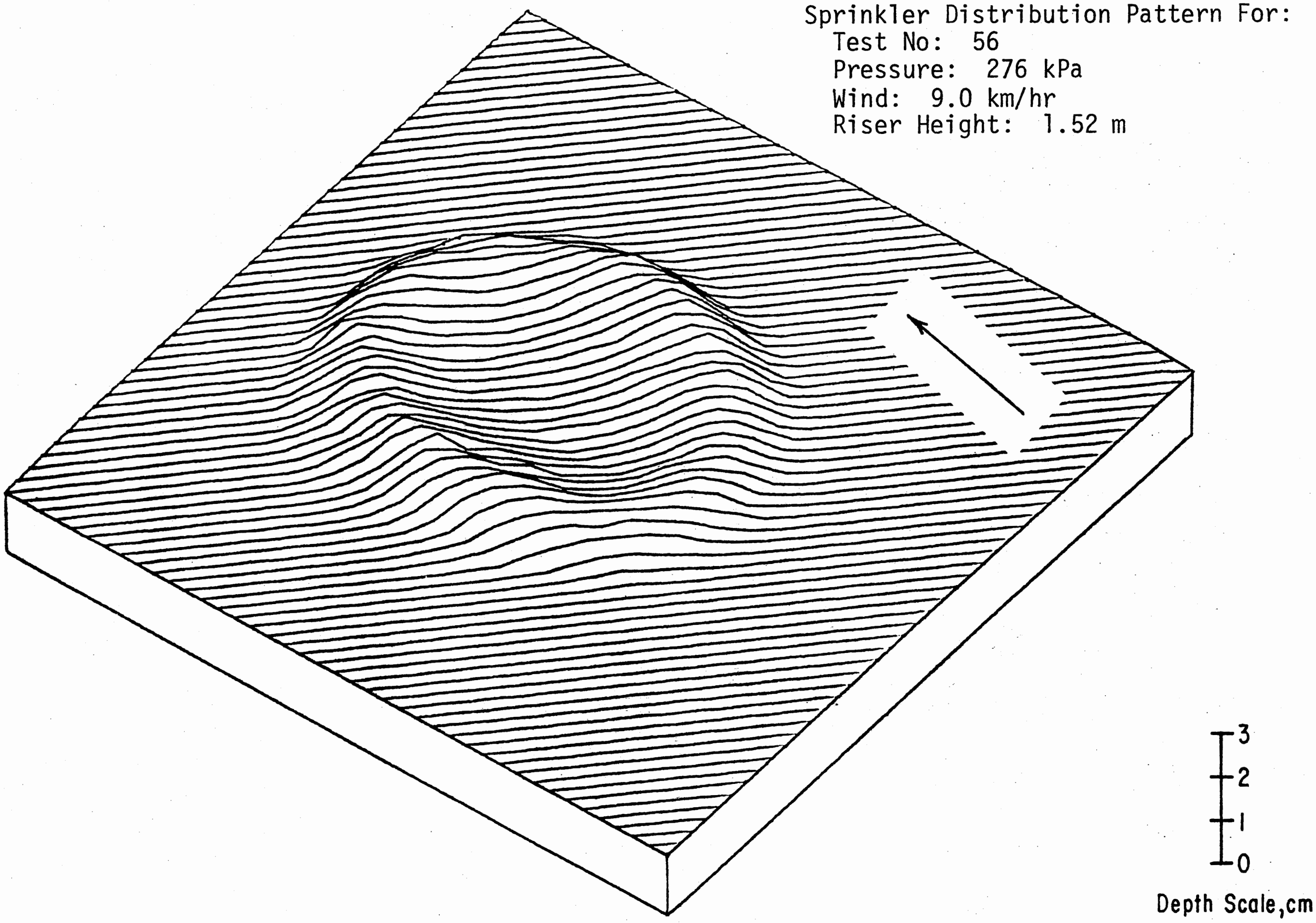

Sprinkler Distribution Pattern For:
Test No: 93
Pressure: 414 kPa
Wind: 9.9 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm

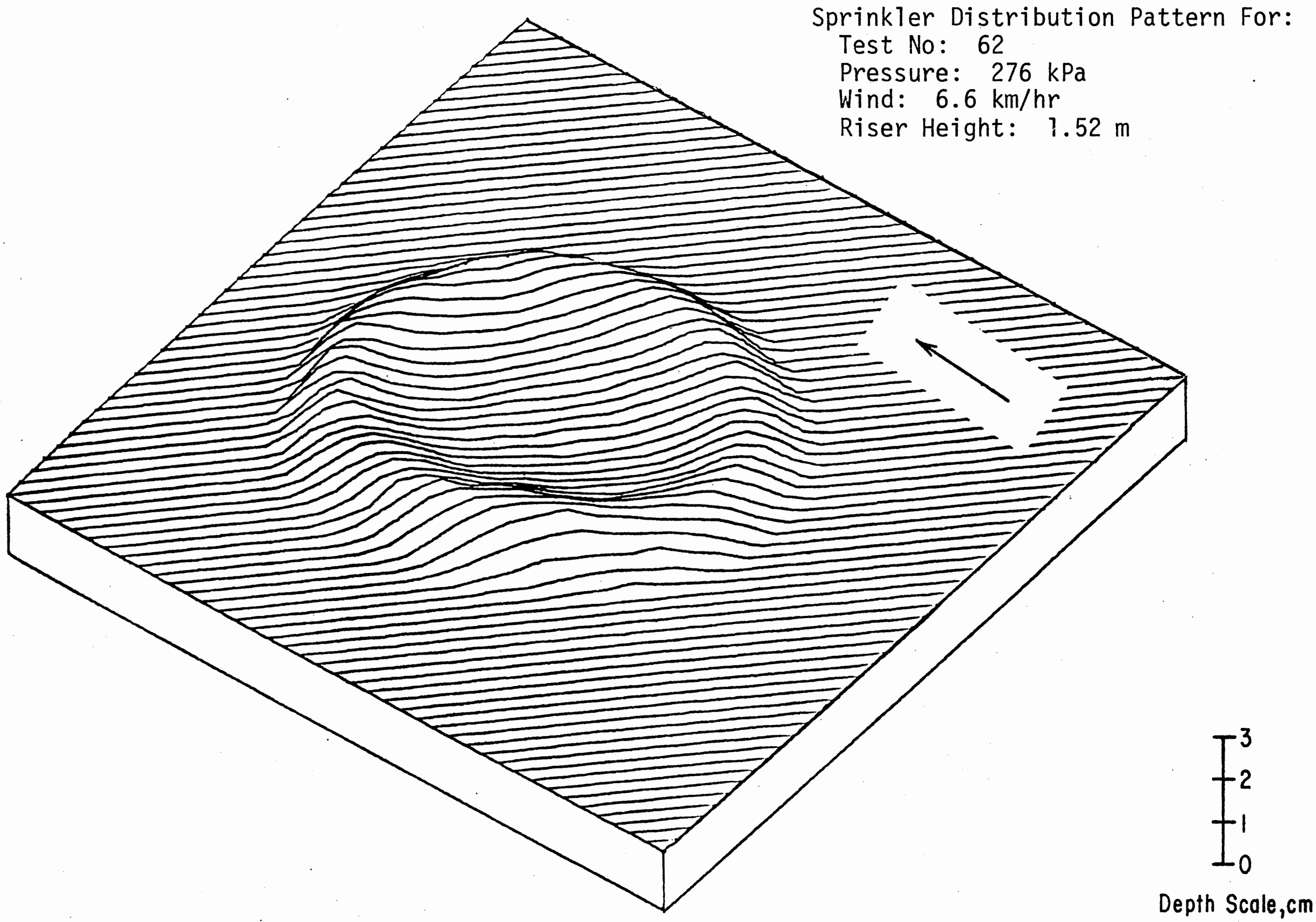

Sprinkler Distribution Pattern For:
Test No: 25
Pressure: 138 kPa
Wind: 6.1 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm

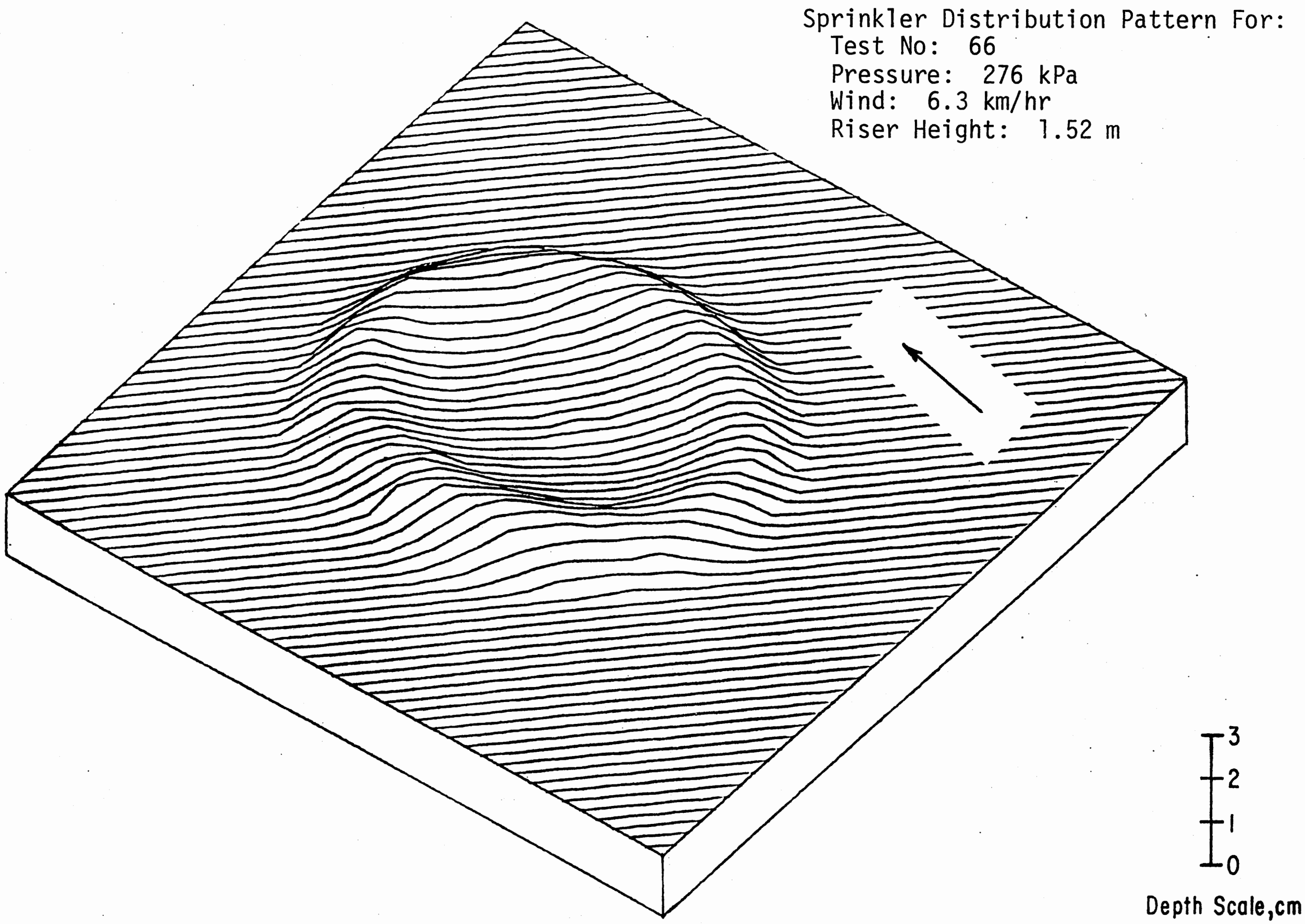


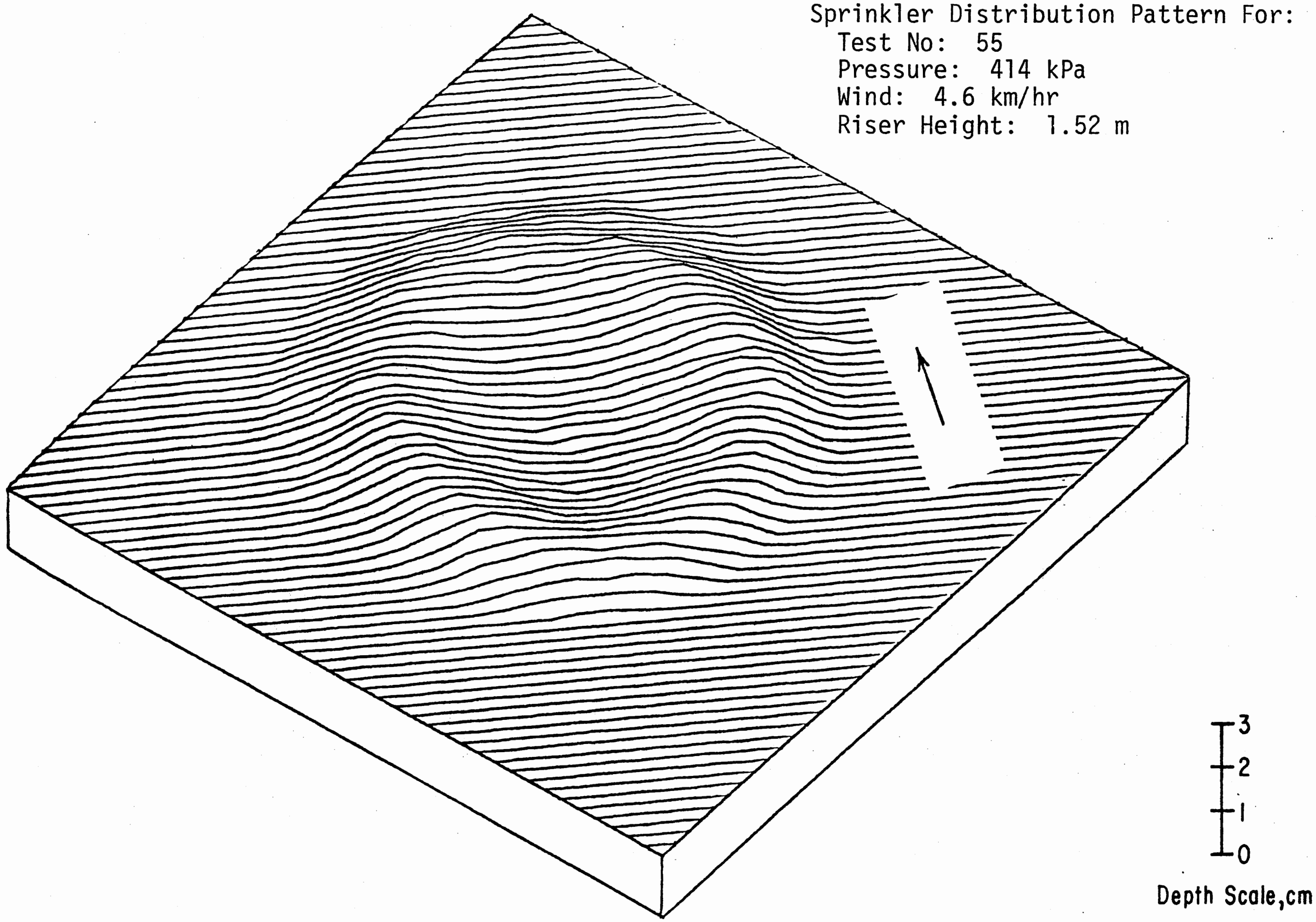
Sprinkler Distribution Pattern For:
Test No: 63
Pressure: 138 kPa
Wind: 7.3 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm


Sprinkler Distribution Pattern For:
Test No: 65
Pressure: 138 kPa
Wind: 9.1 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm


Sprinkler Distribution Pattern For:
Test No: 56
Pressure: 276 kPa
Wind: 9.0 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm

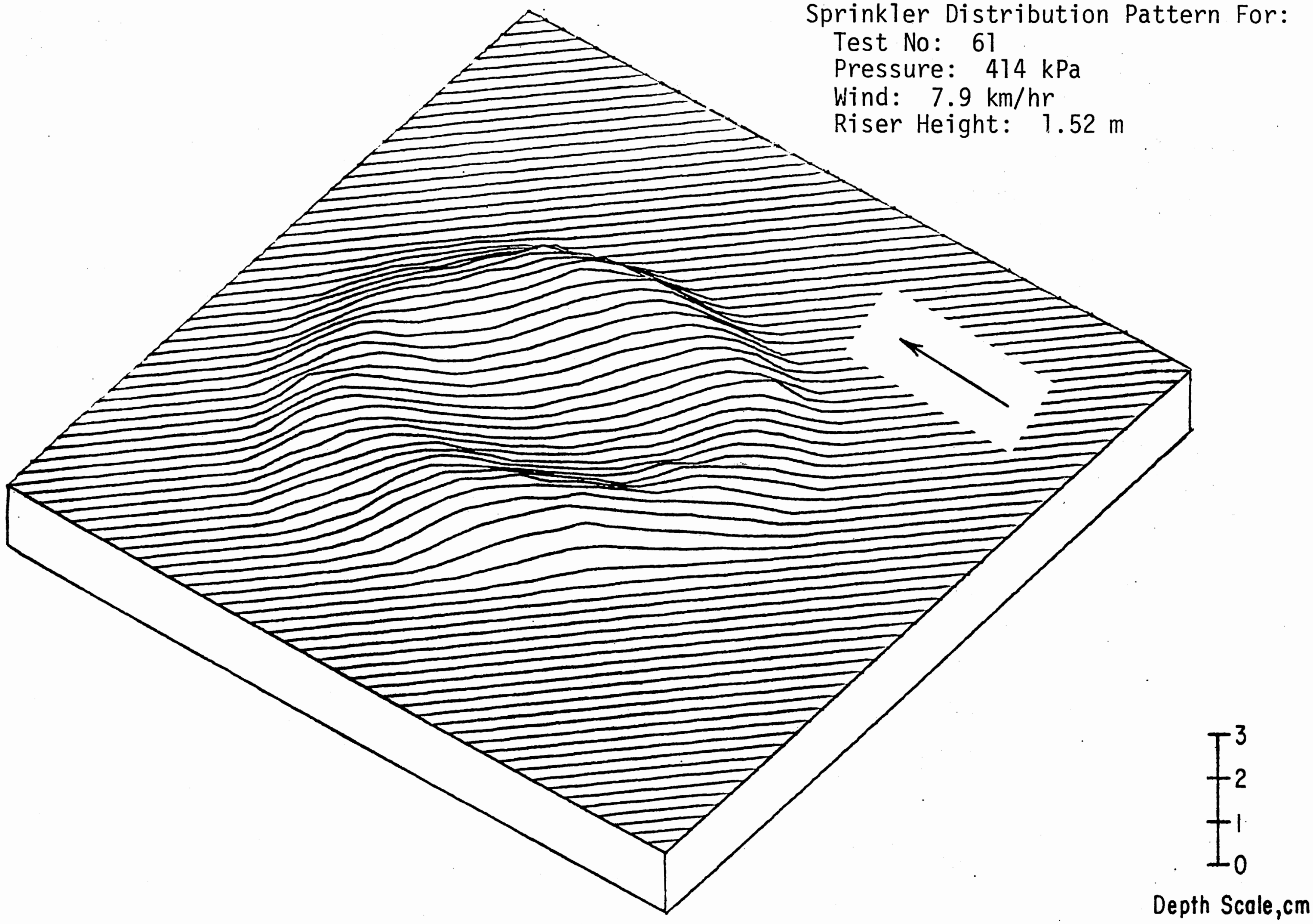

Sprinkler Distribution Pattern For:
Test No: 62
Pressure: 276 kPa
Wind: 6.6 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm


Sprinkler Distribution Pattern For:
Test No: 66
Pressure: 276 kPa
Wind: 6.3 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm

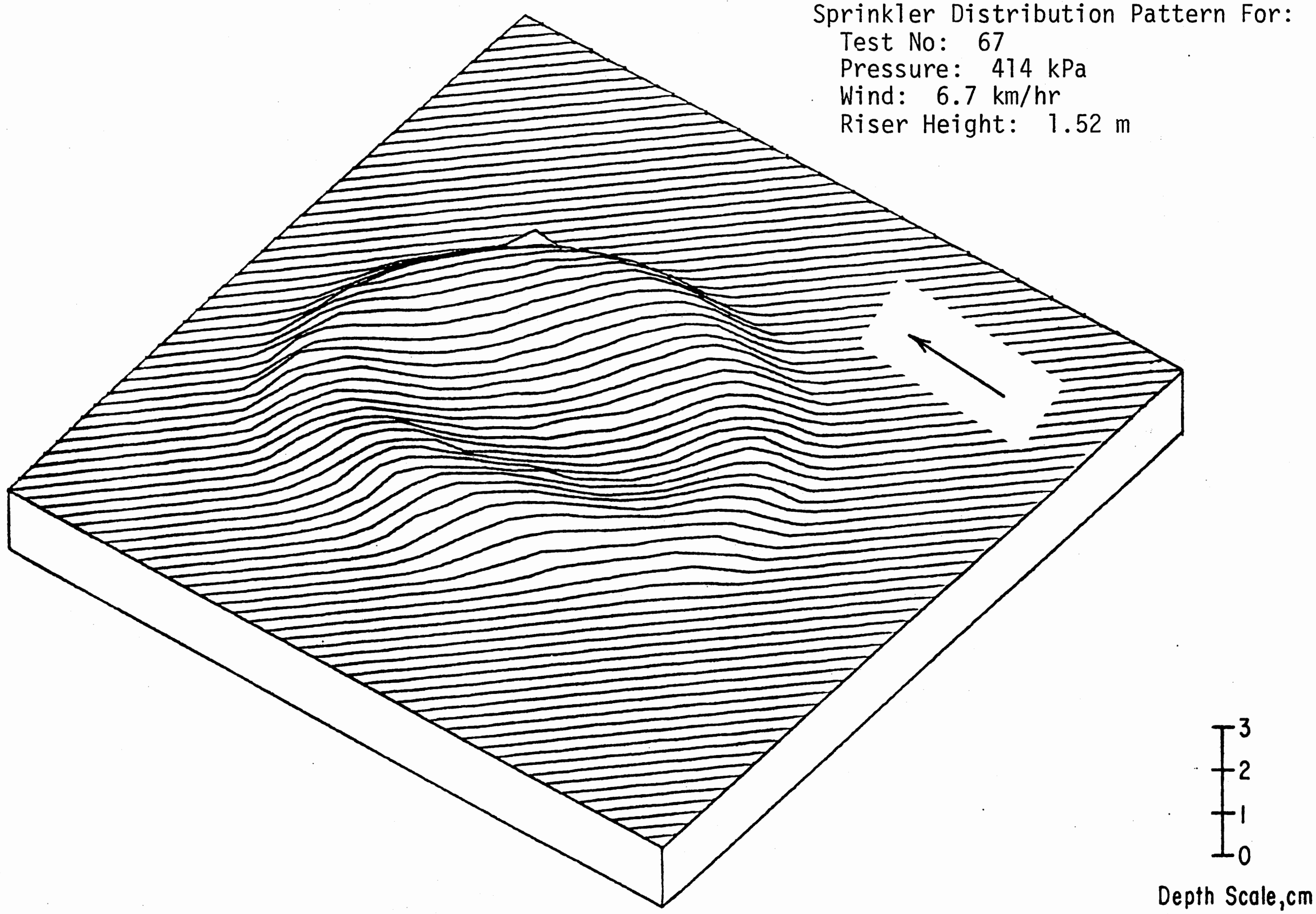


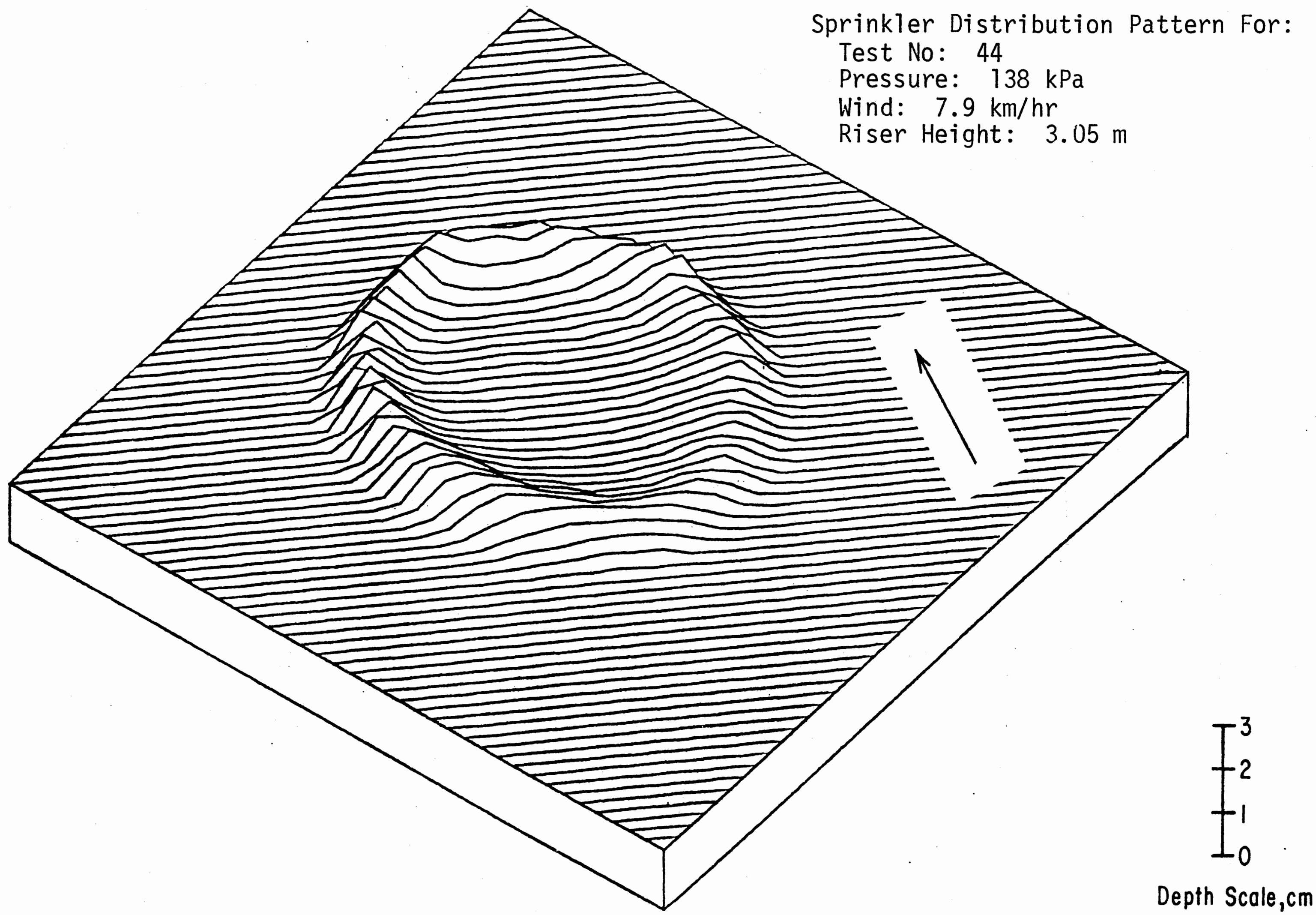
Sprinkler Distribution Pattern For:
Test No: 55
Pressure: 414 kPa
Wind: 4.6 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm

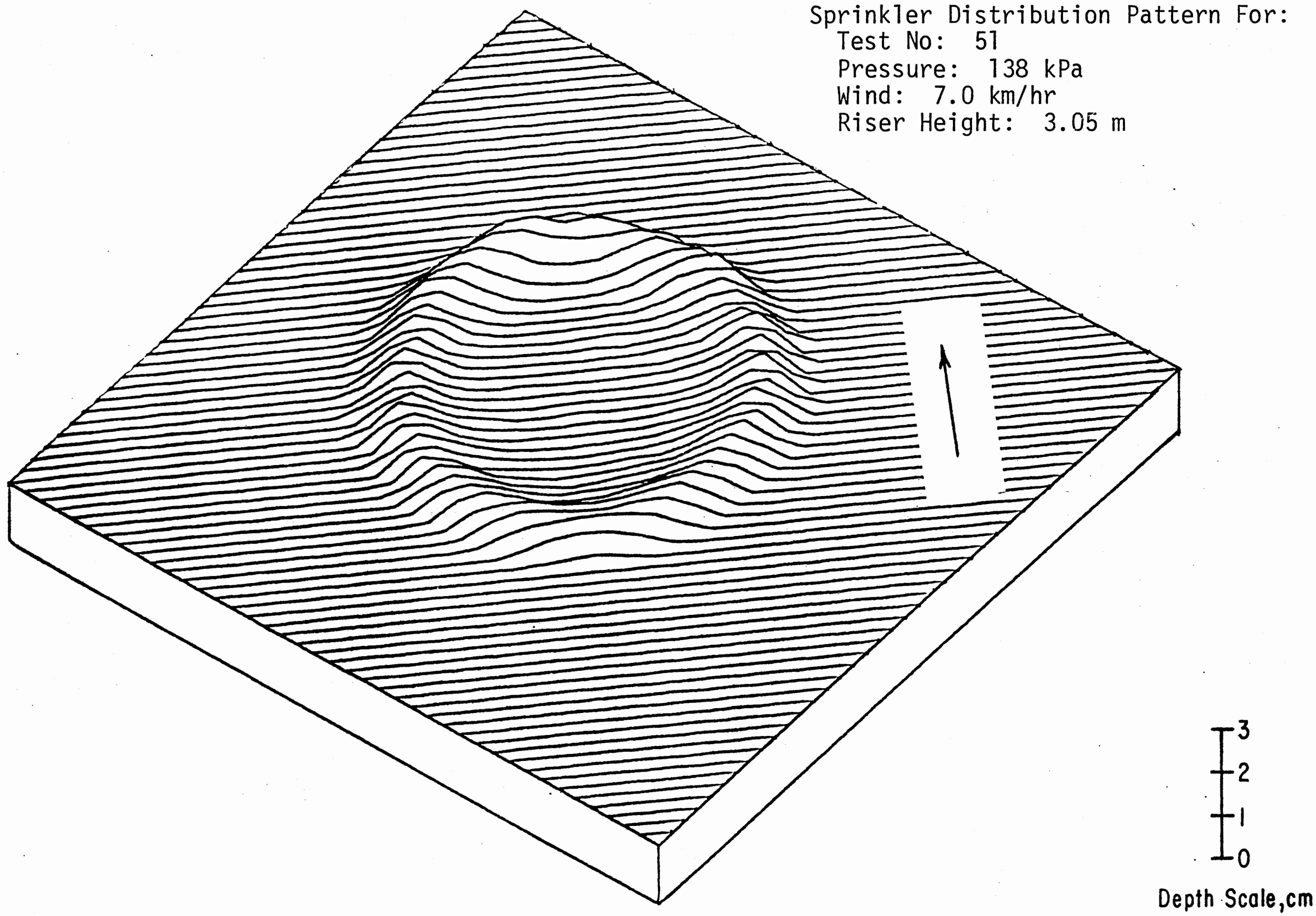
Sprinkler Distribution Pattern For:
Test No: 61
Pressure: 414 kPa
Wind: 7.9 km/hr
Riser Height: 1.52 m



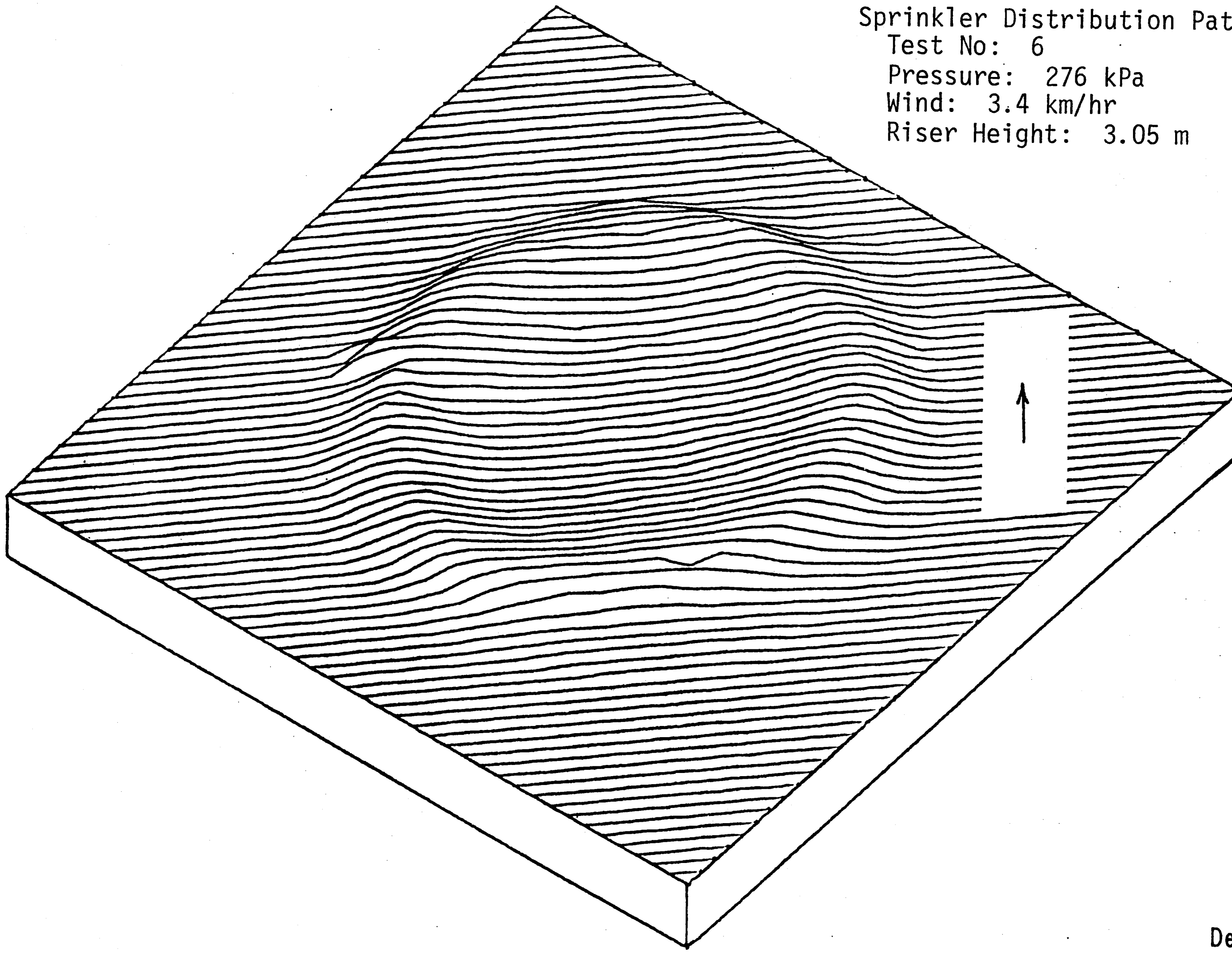
Sprinkler Distribution Pattern For:
Test No: 67
Pressure: 414 kPa
Wind: 6.7 km/hr
Riser Height: 1.52 m

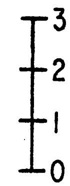



Sprinkler Distribution Pattern For:
Test No: 44
Pressure: 138 kPa
Wind: 7.9 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm


Sprinkler Distribution Pattern For:
Test No: 51
Pressure: 138 kPa
Wind: 7.0 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm

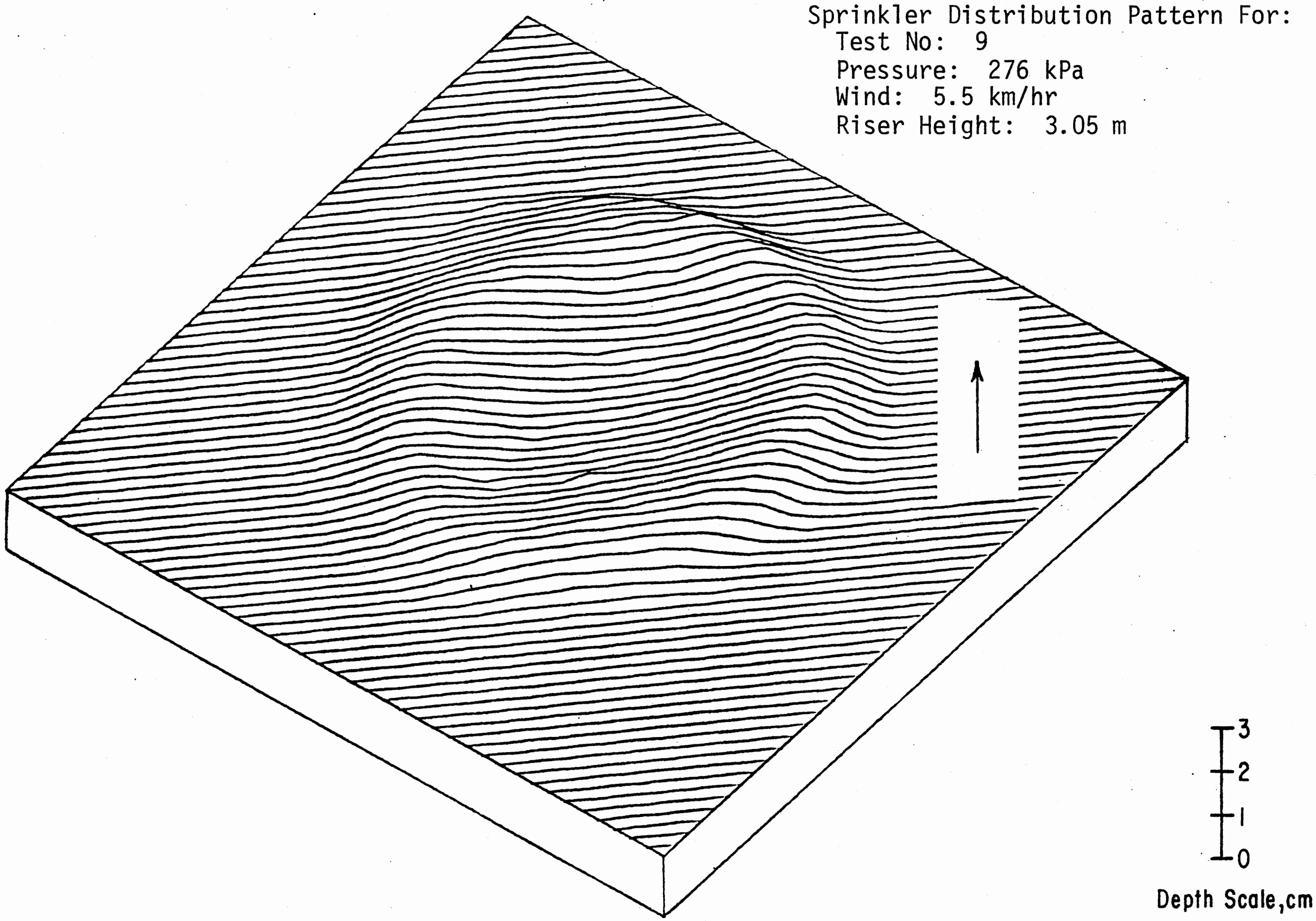
Sprinkler Distribution Pattern For:
Test No: 6
Pressure: 276 kPa
Wind: 3.4 km/hr
Riser Height: 3.05 m



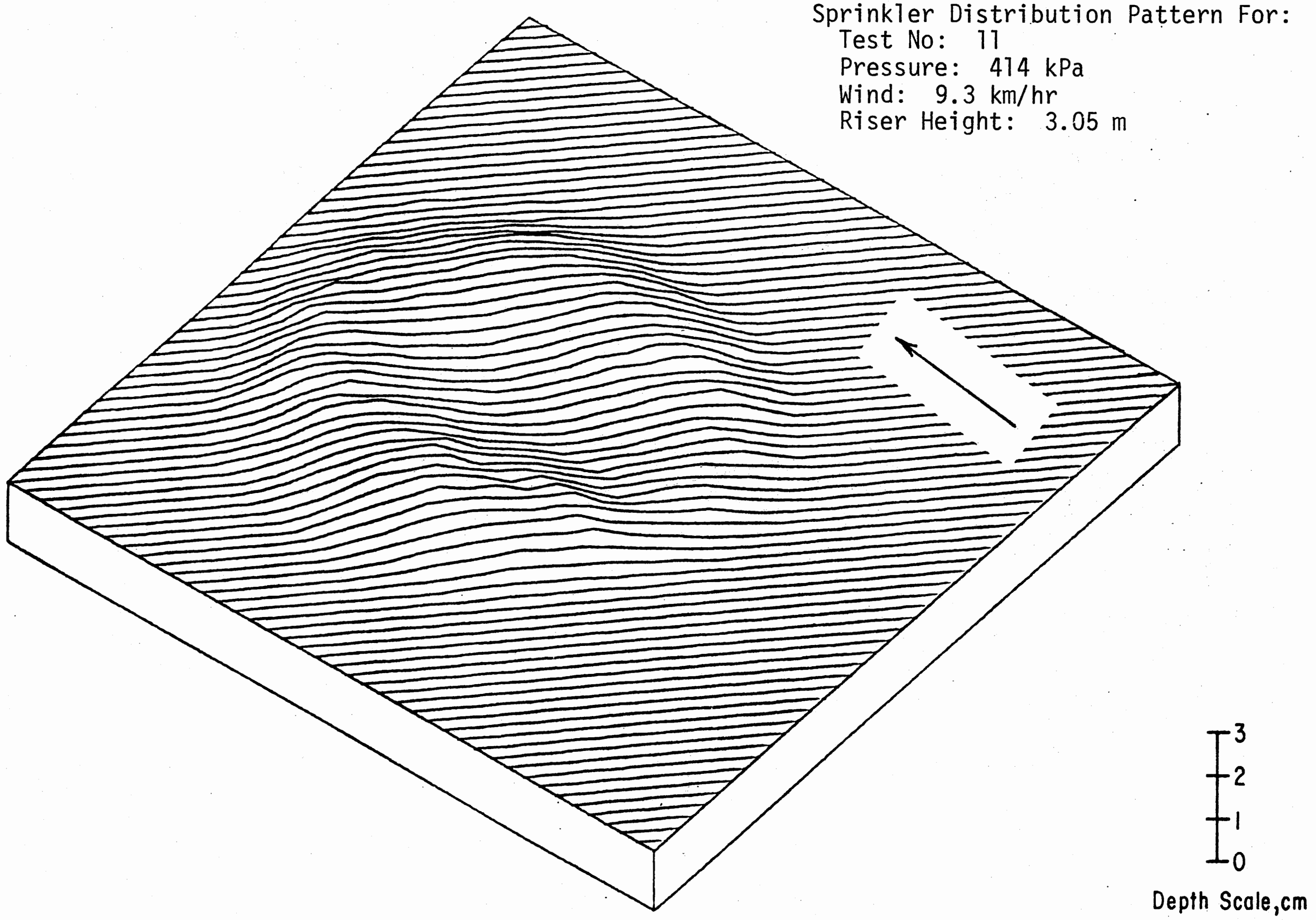


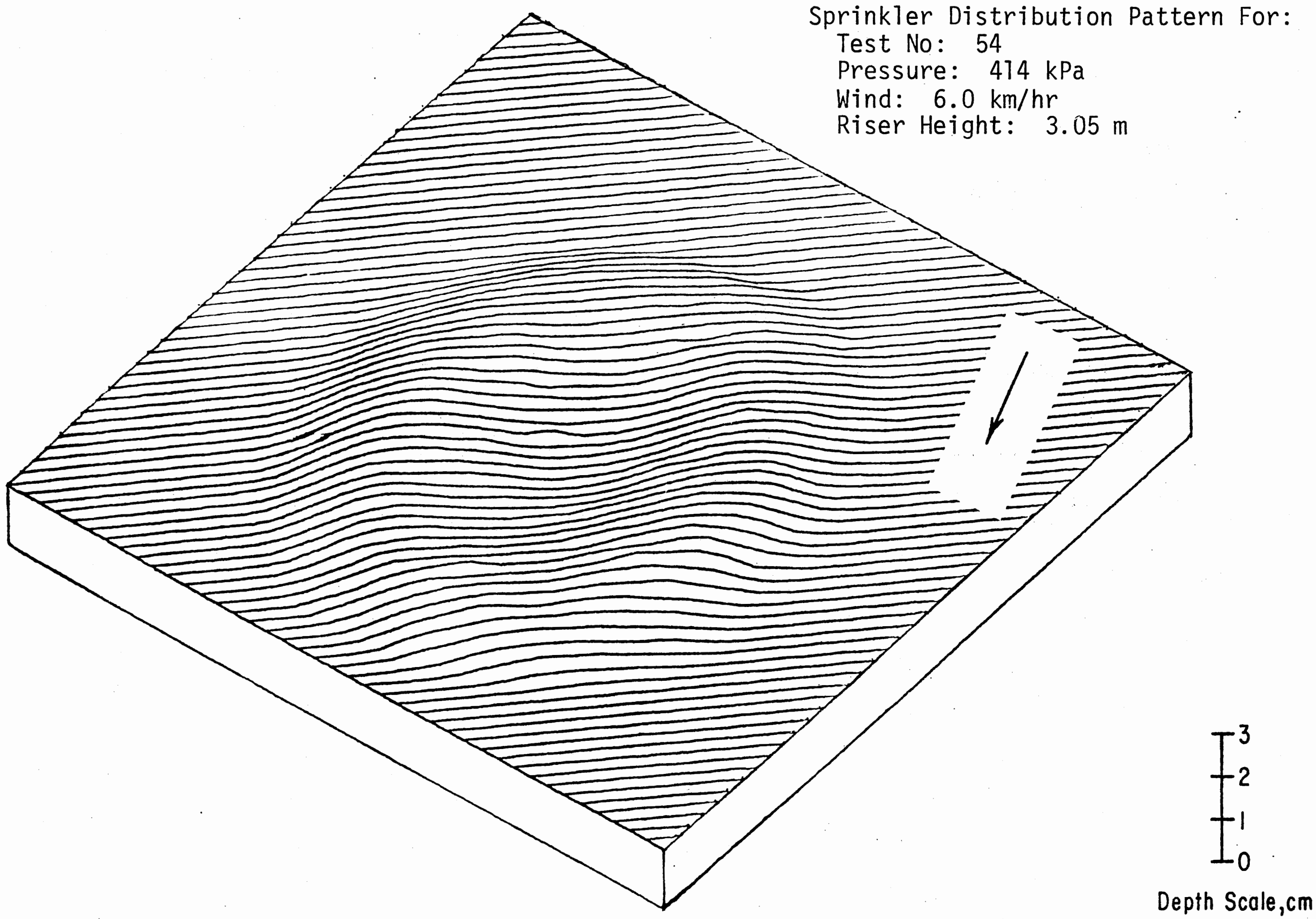
Depth Scale,cm

Sprinkler Distribution Pattern For:
Test No: 9
Pressure: 276 kPa
Wind: 5.5 km/hr
Riser Height: 3.05 m

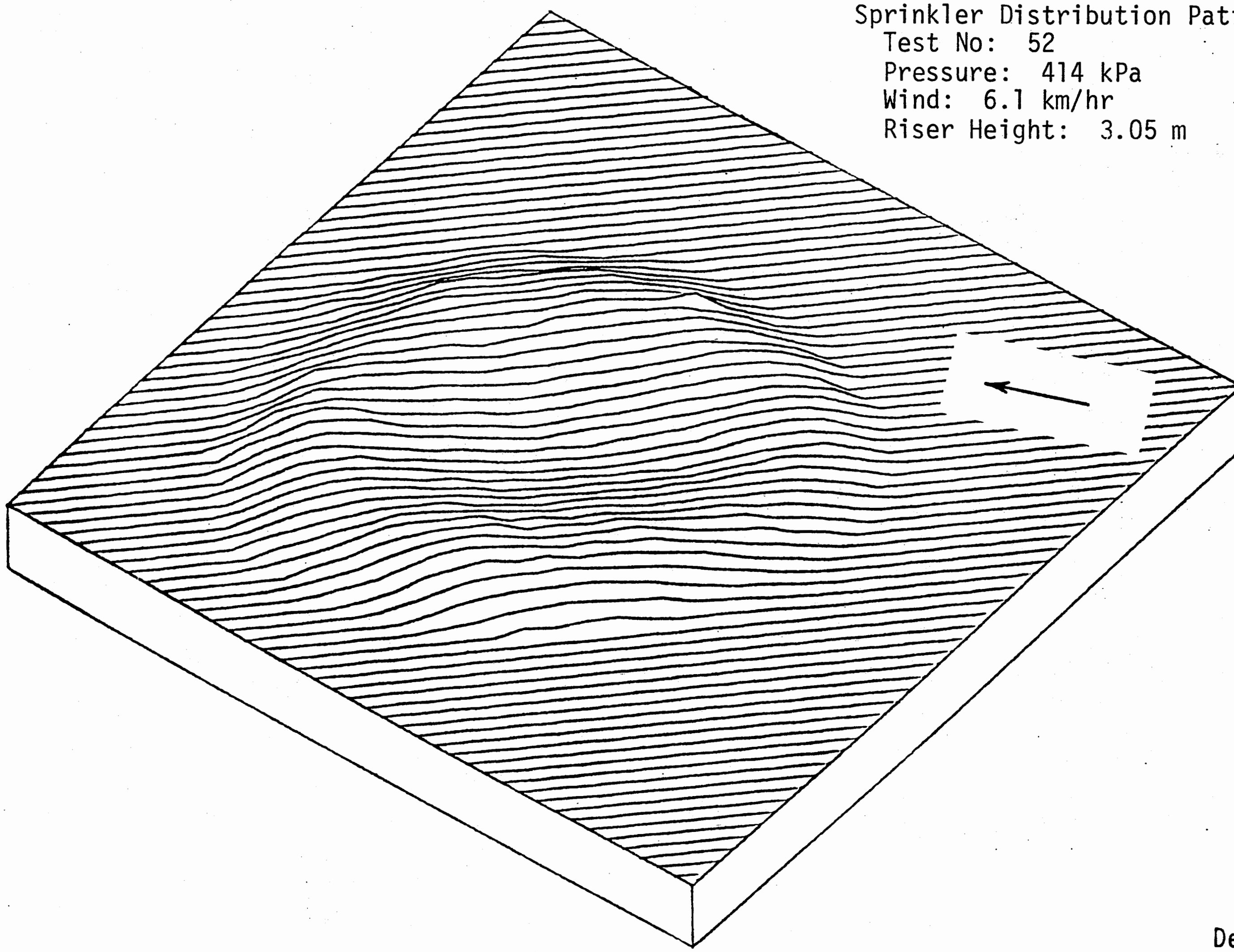


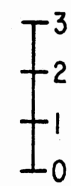
Sprinkler Distribution Pattern For:
Test No: 11
Pressure: 414 kPa
Wind: 9.3 km/hr
Riser Height: 3.05 m




Sprinkler Distribution Pattern For:
Test No: 54
Pressure: 414 kPa
Wind: 6.0 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm

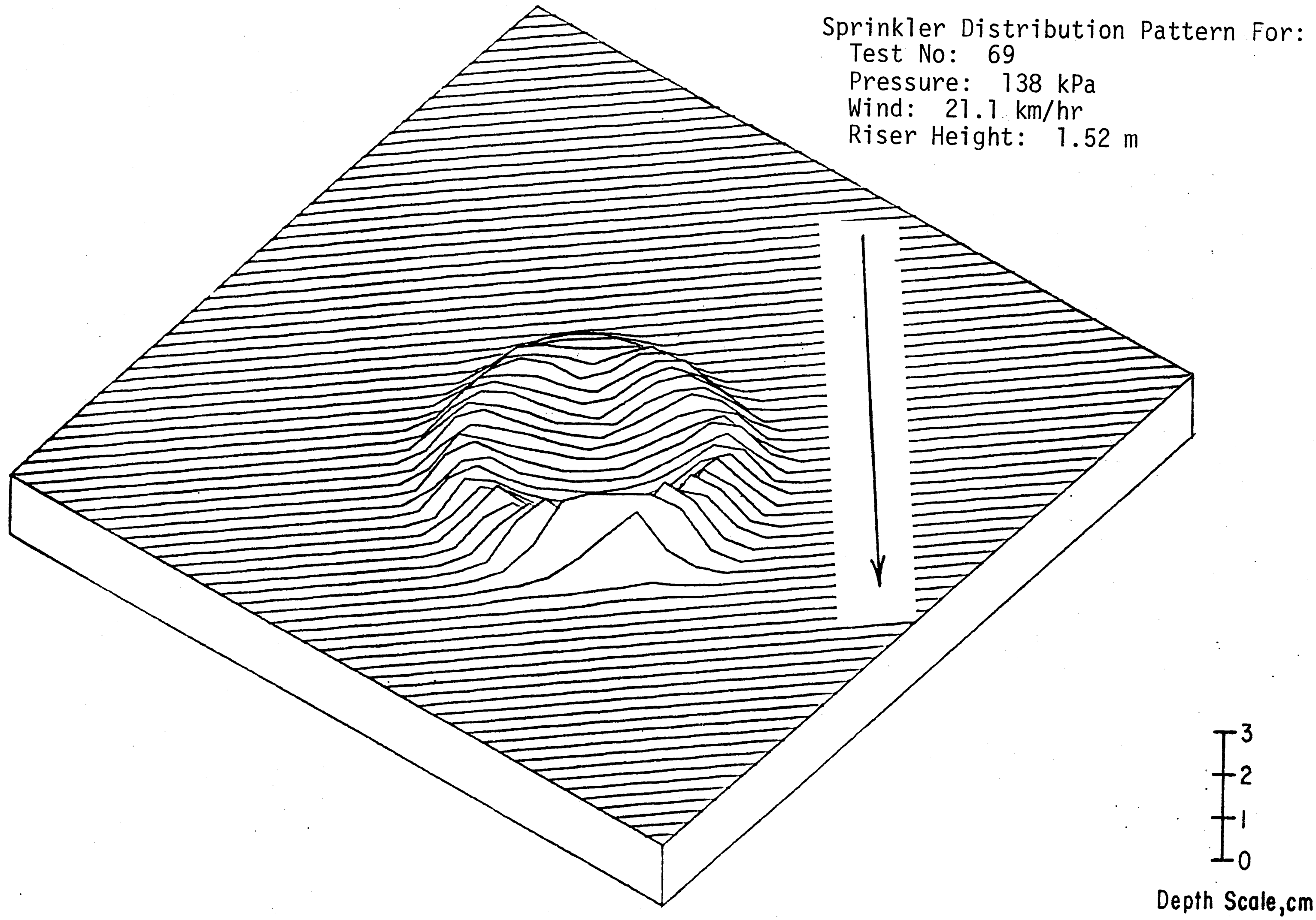
Sprinkler Distribution Pattern For:
Test No: 52
Pressure: 414 kPa
Wind: 6.1 km/hr
Riser Height: 3.05 m



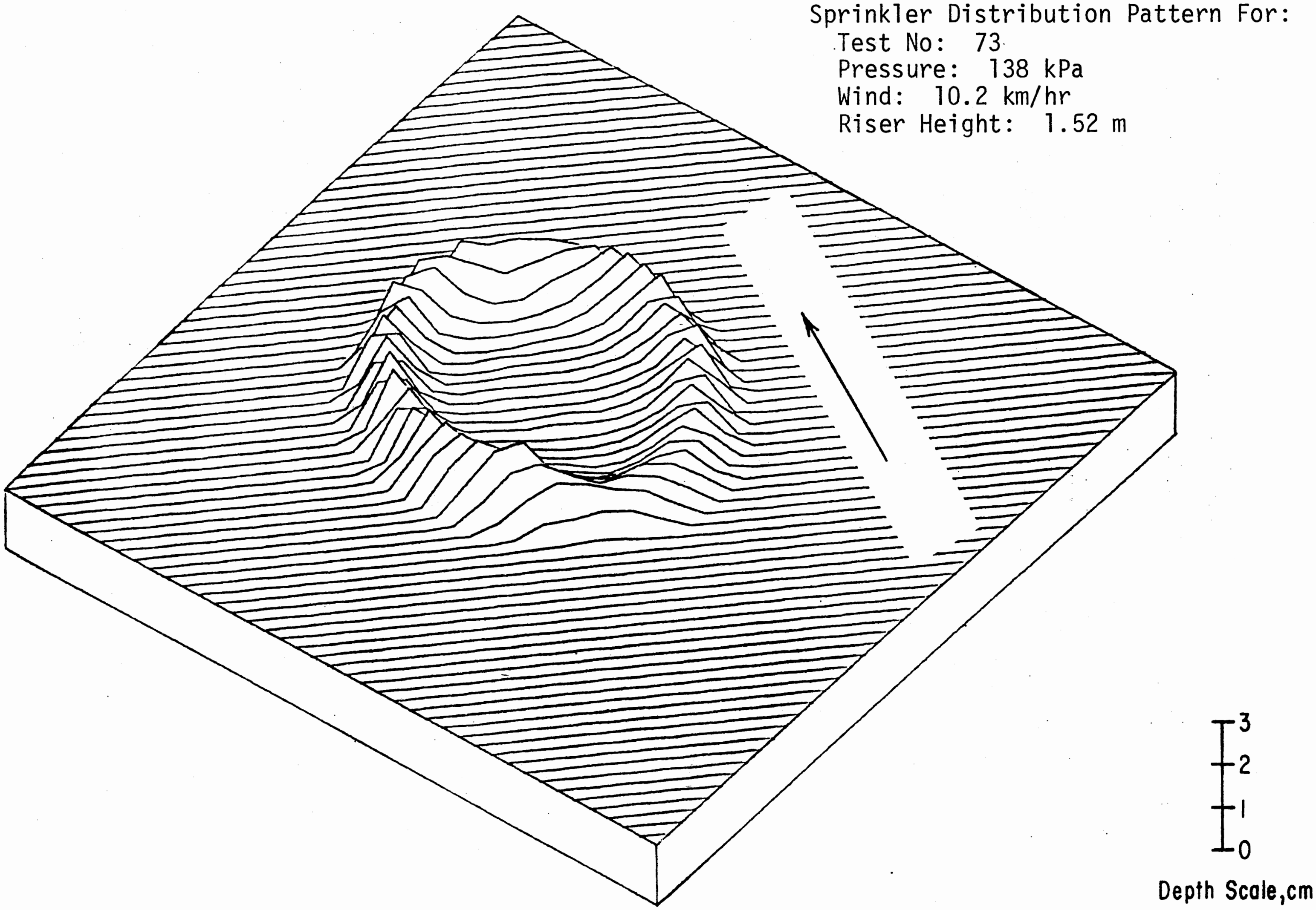


Depth Scale,cm

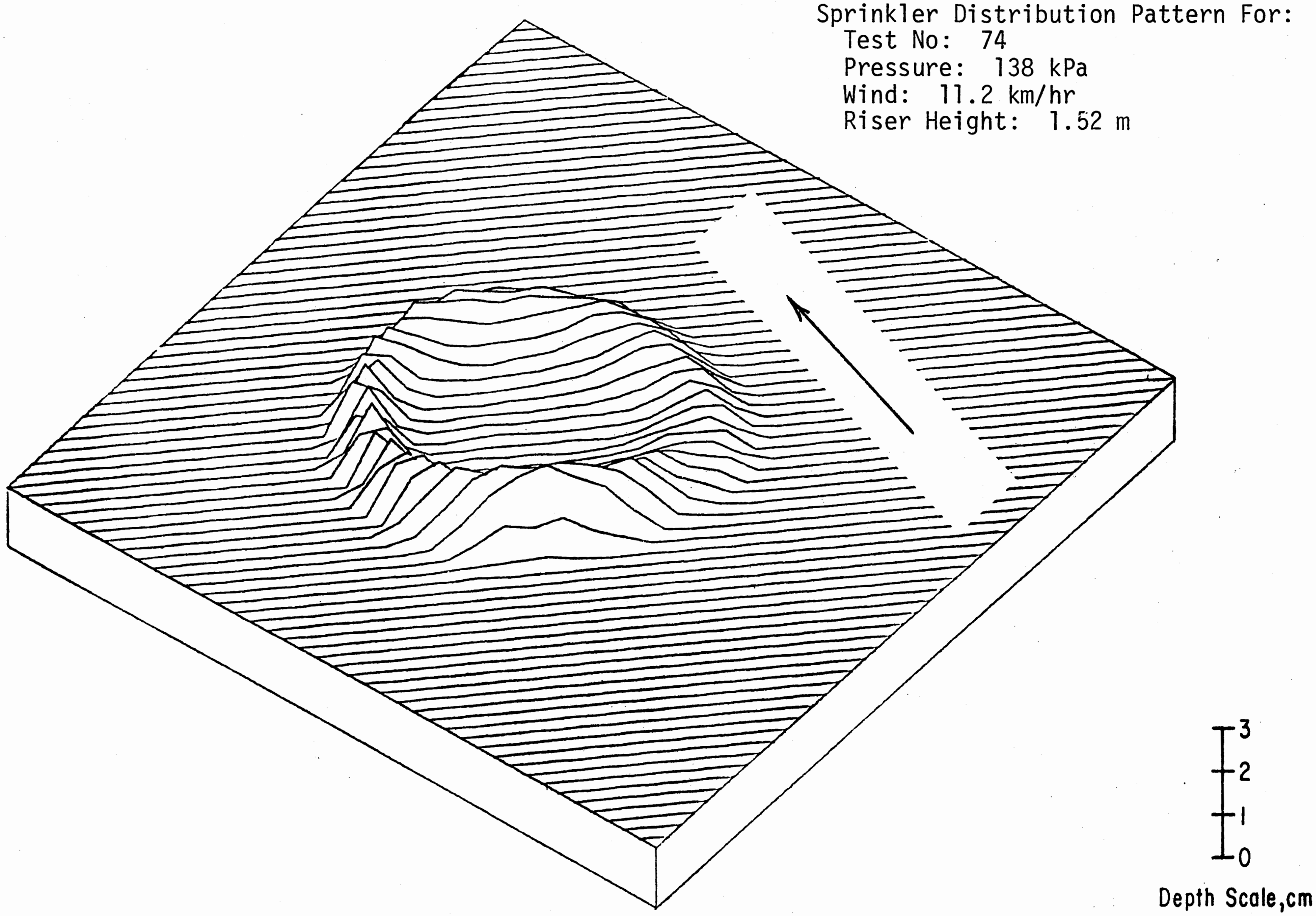
Sprinkler Distribution Pattern For:
Test No: 69
Pressure: 138 kPa
Wind: 21.1 km/hr
Riser Height: 1.52 m

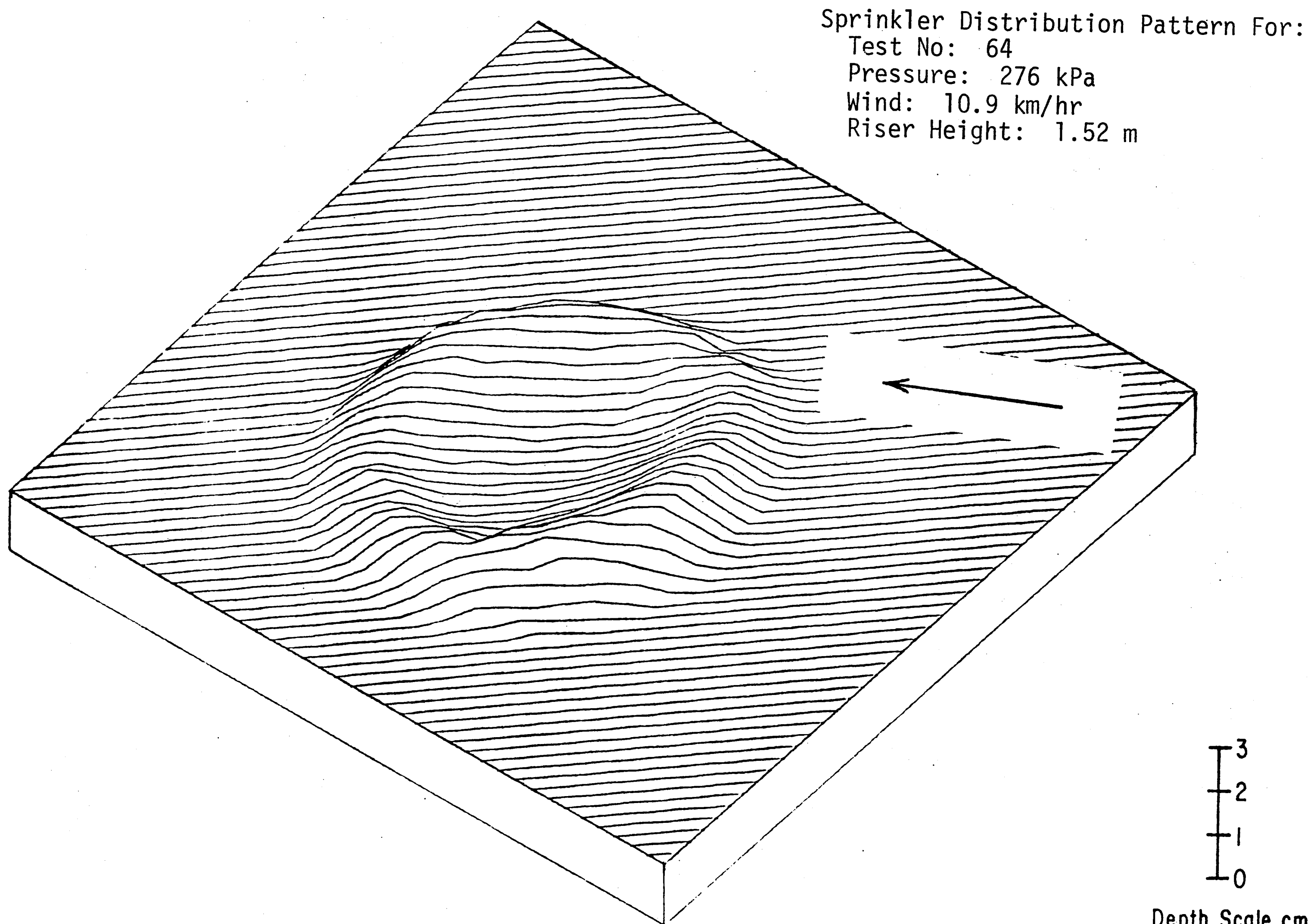


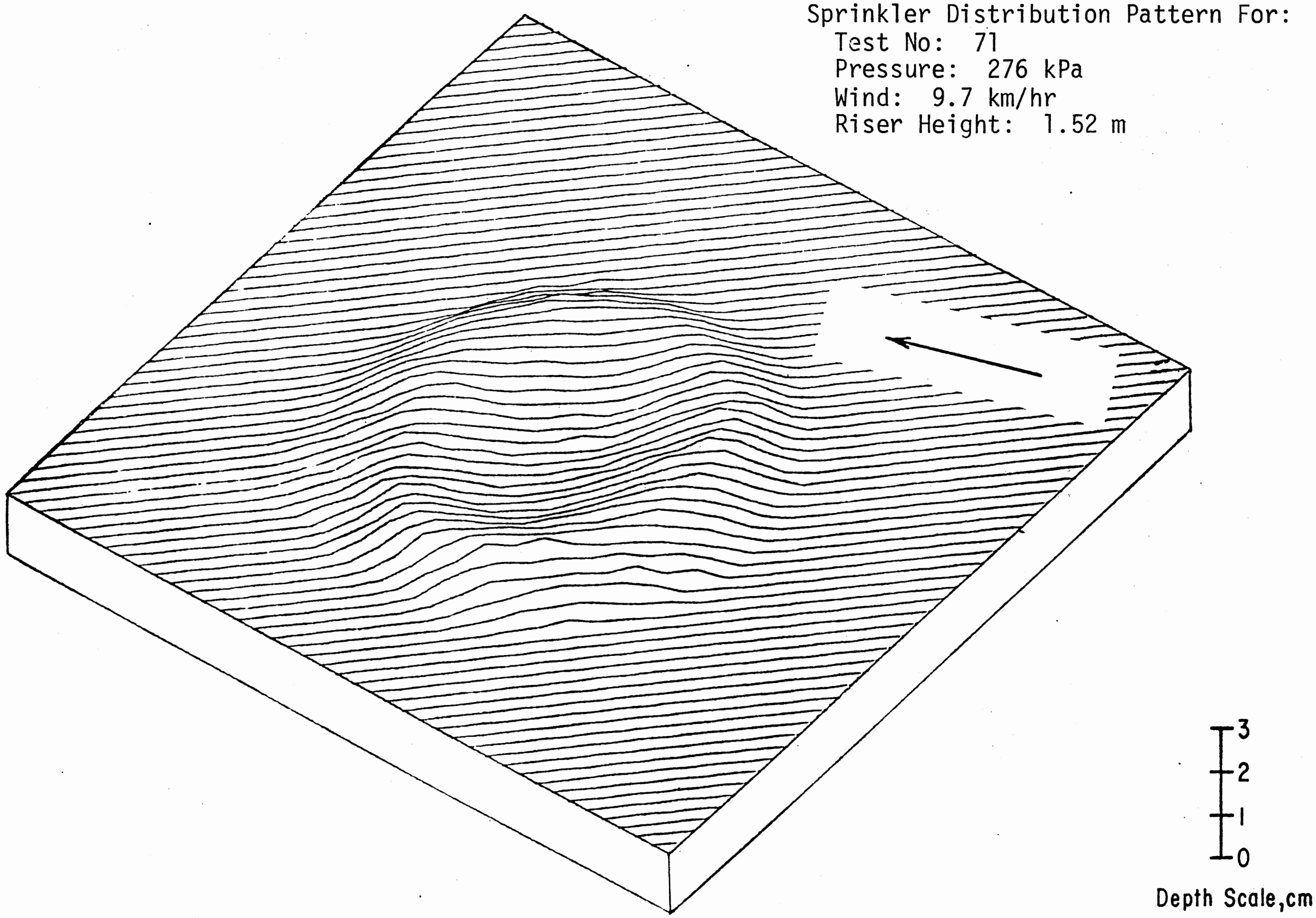
Sprinkler Distribution Pattern For:
Test No: 73
Pressure: 138 kPa
Wind: 10.2 km/hr
Riser Height: 1.52 m



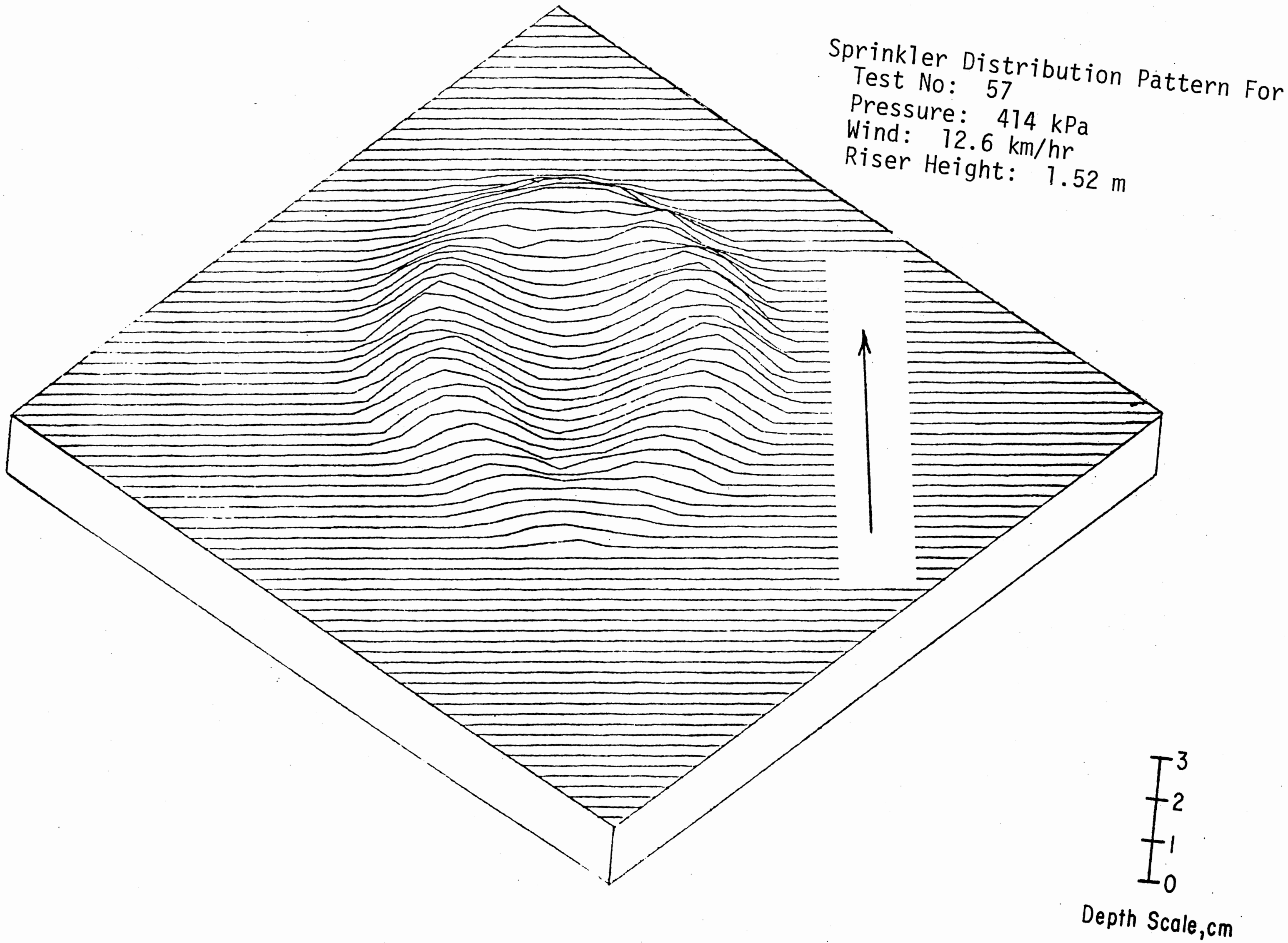
Sprinkler Distribution Pattern For:
Test No: 74
Pressure: 138 kPa
Wind: 11.2 km/hr
Riser Height: 1.52 m

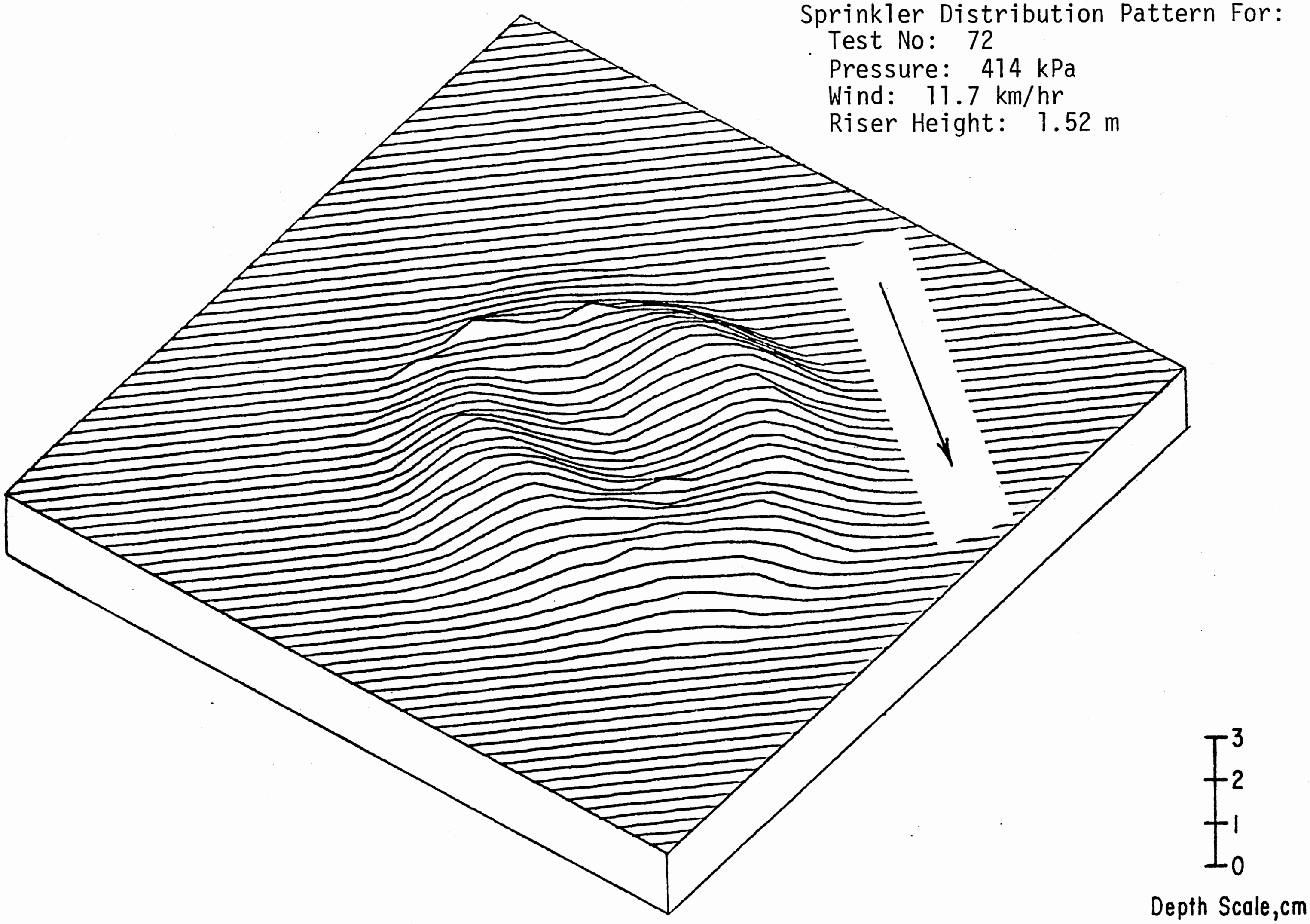


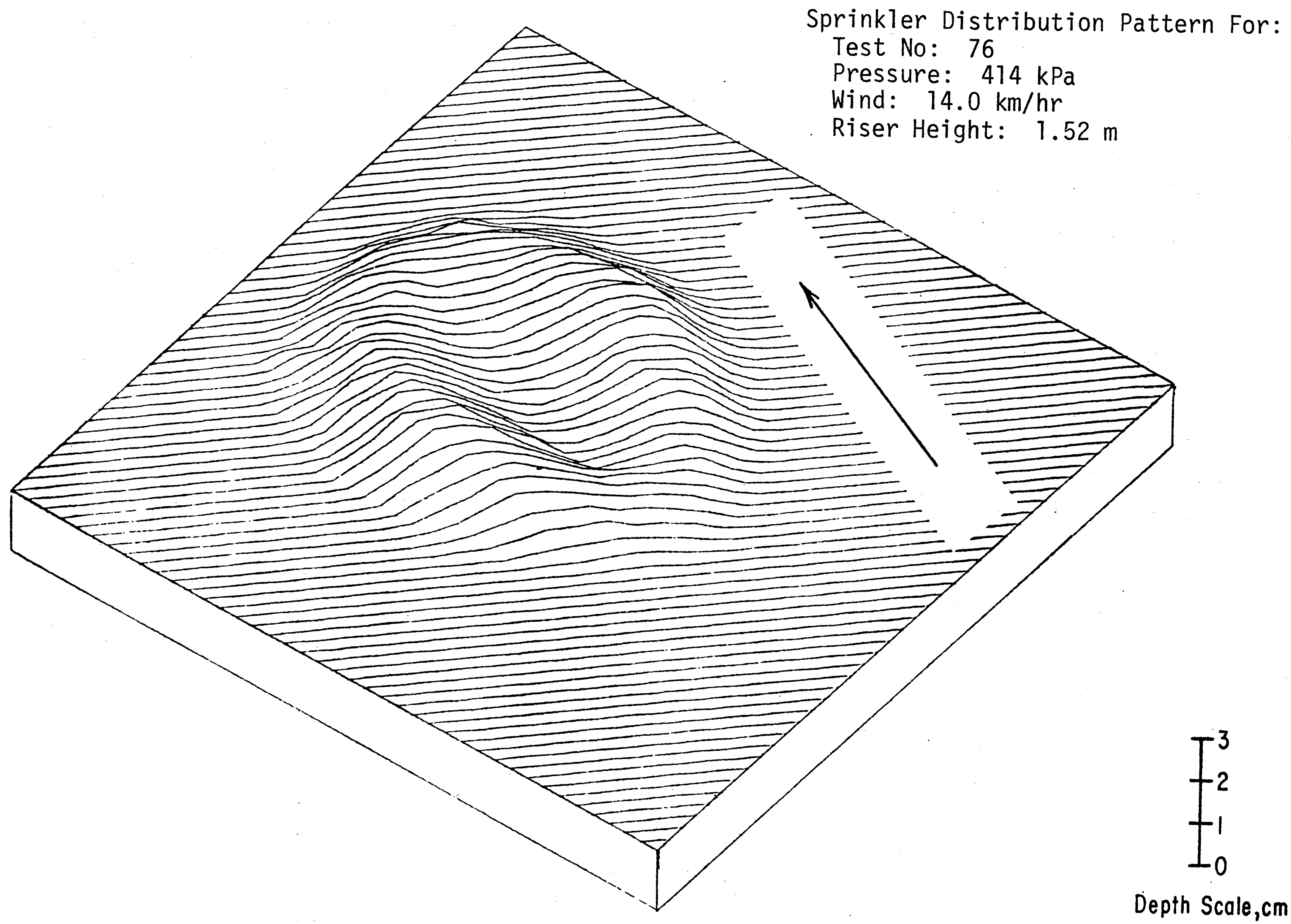

Sprinkler Distribution Pattern For:
Test No: 64
Pressure: 276 kPa
Wind: 10.9 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm



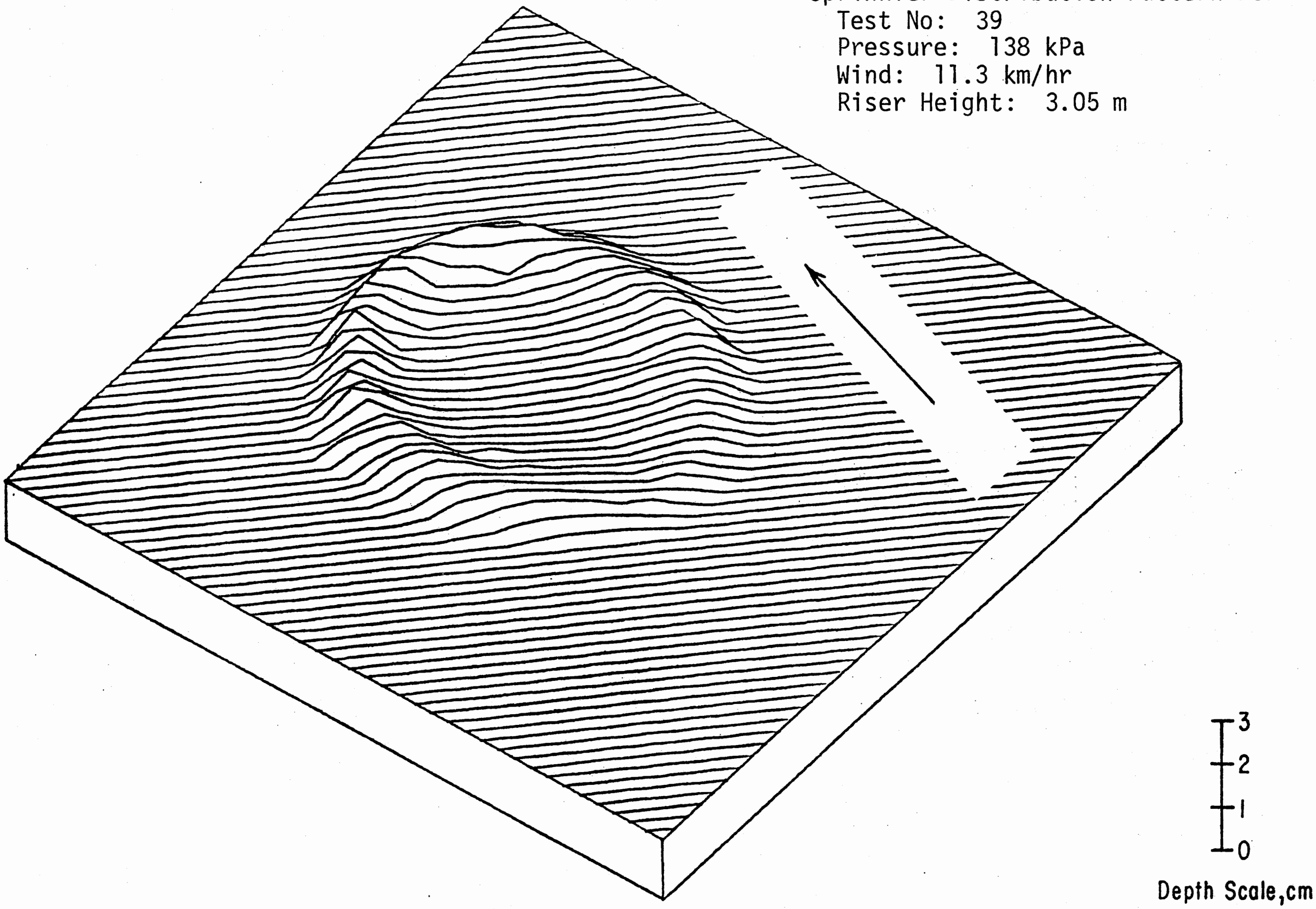
Sprinkler Distribution Pattern For:
Test No: 71
Pressure: 276 kPa
Wind: 9.7 km/hr
Riser Height: 1.52 m


Sprinkler Distribution Pattern For:
Test No: 57
Pressure: 414 kPa
Wind: 12.6 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm

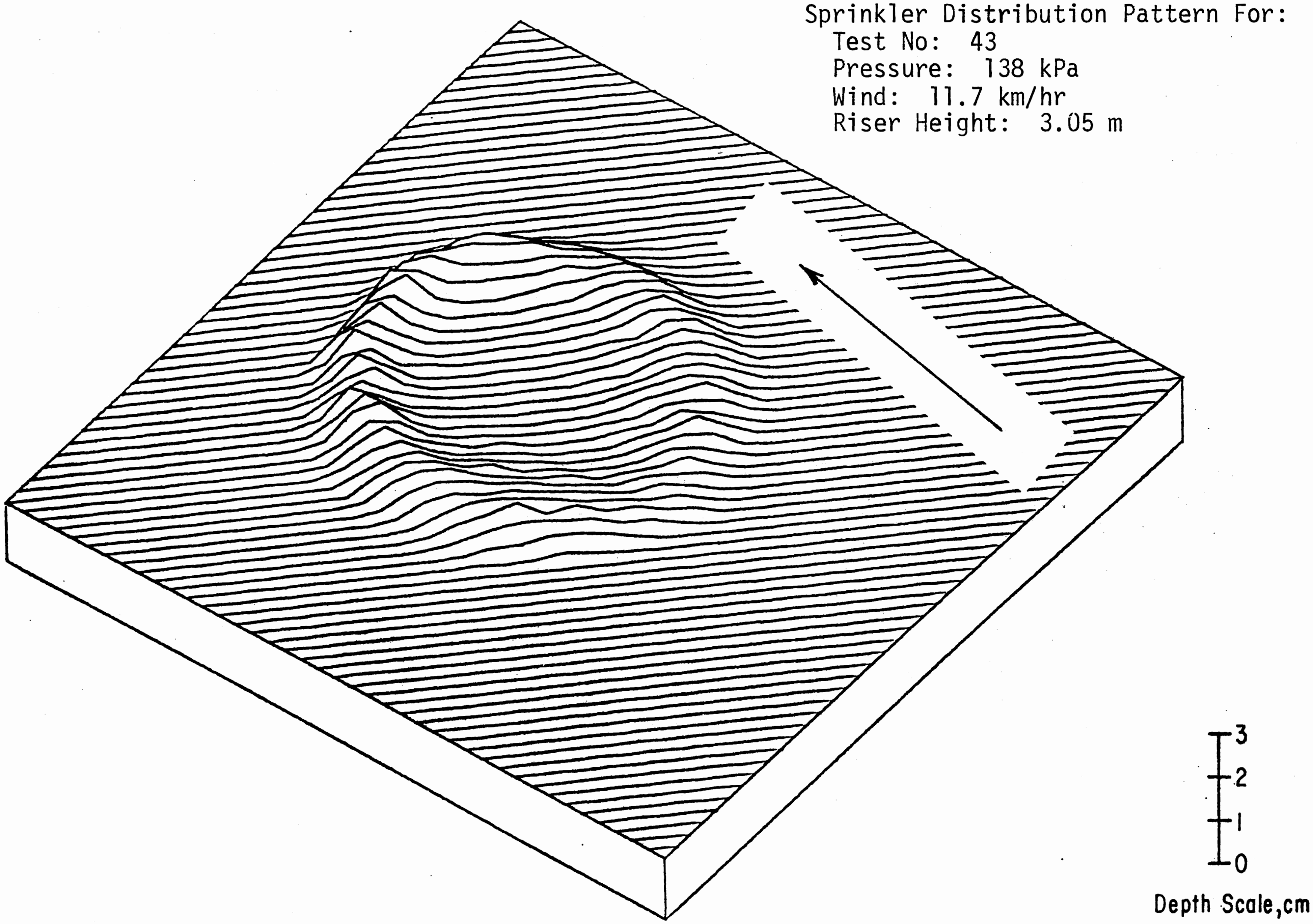

Sprinkler Distribution Pattern For:
Test No: 72
Pressure: 414 kPa
Wind: 11.7 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm


Sprinkler Distribution Pattern For:
Test No: 76
Pressure: 414 kPa
Wind: 14.0 km/hr
Riser Height: 1.52 m
3
2
1
0
Depth Scale,cm

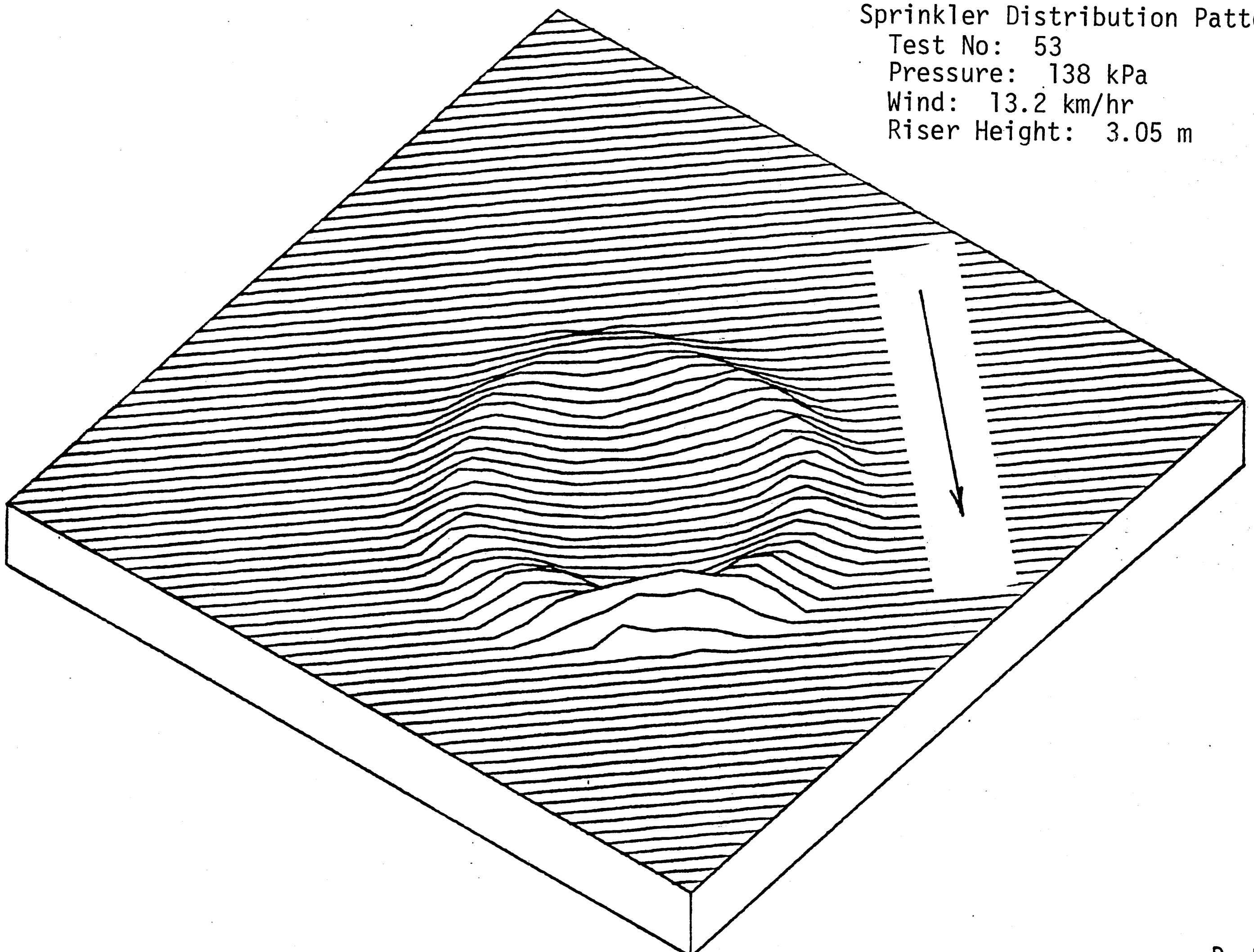
Sprinkler Distribution Pattern For:
Test No: 39
Pressure: 138 kPa
Wind: 11.3 km/hr
Riser Height: 3.05 m

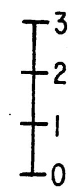


Sprinkler Distribution Pattern For:
Test No: 43
Pressure: 138 kPa
Wind: 11.7 km/hr
Riser Height: 3.05 m

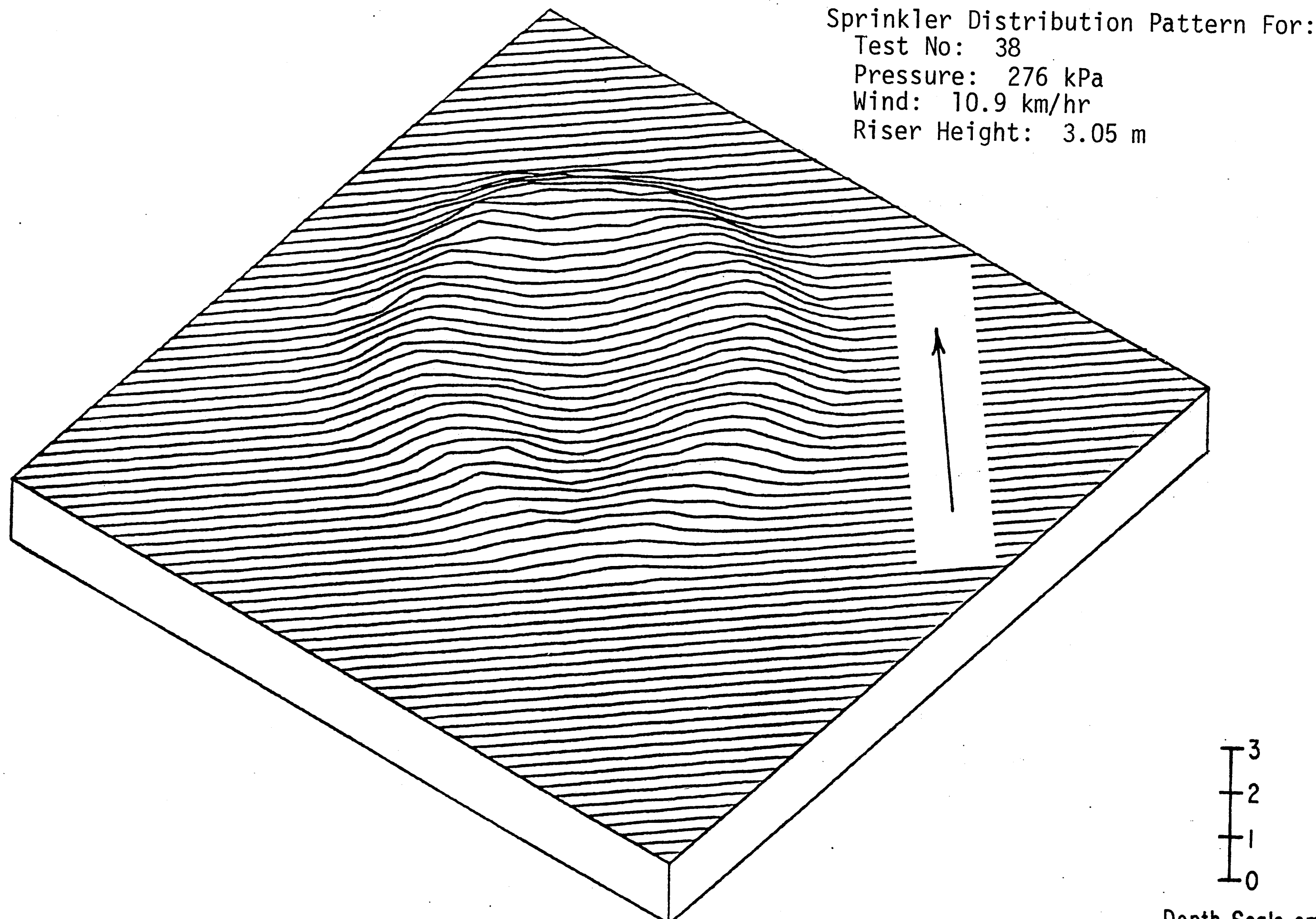


Sprinkler Distribution Pattern For:
Test No: 53
Pressure: 138 kPa
Wind: 13.2 km/hr
Riser Height: 3.05 m

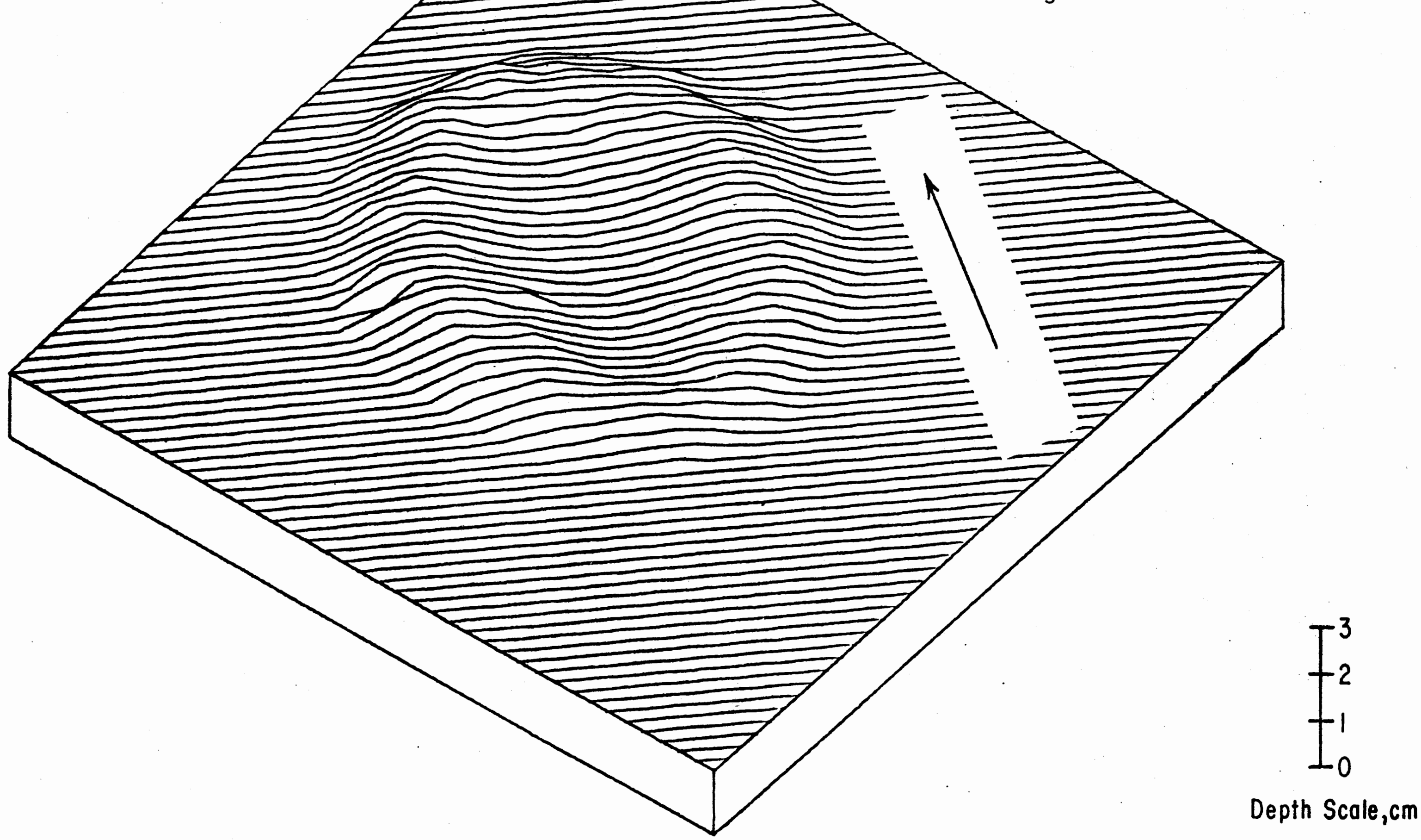


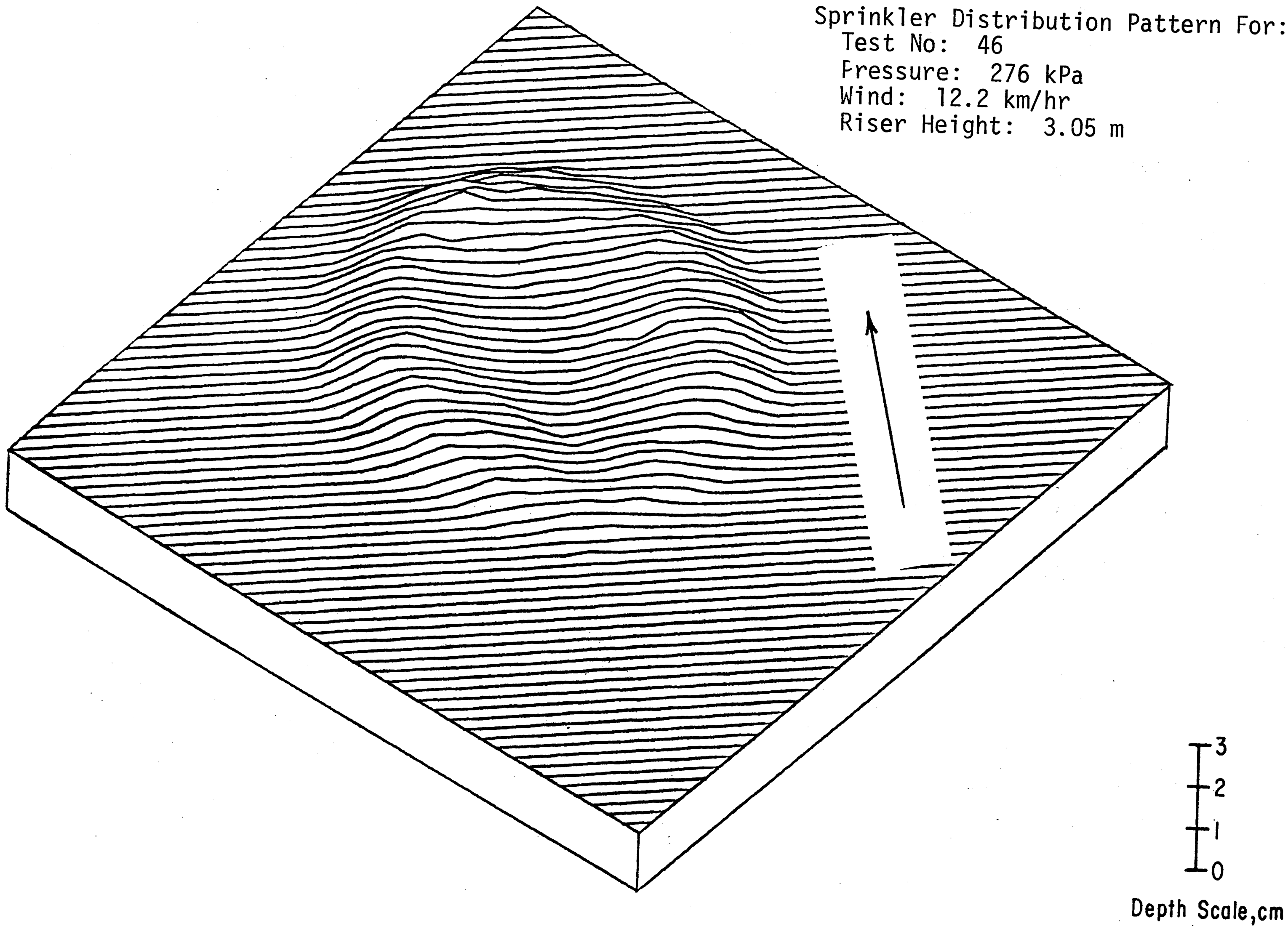


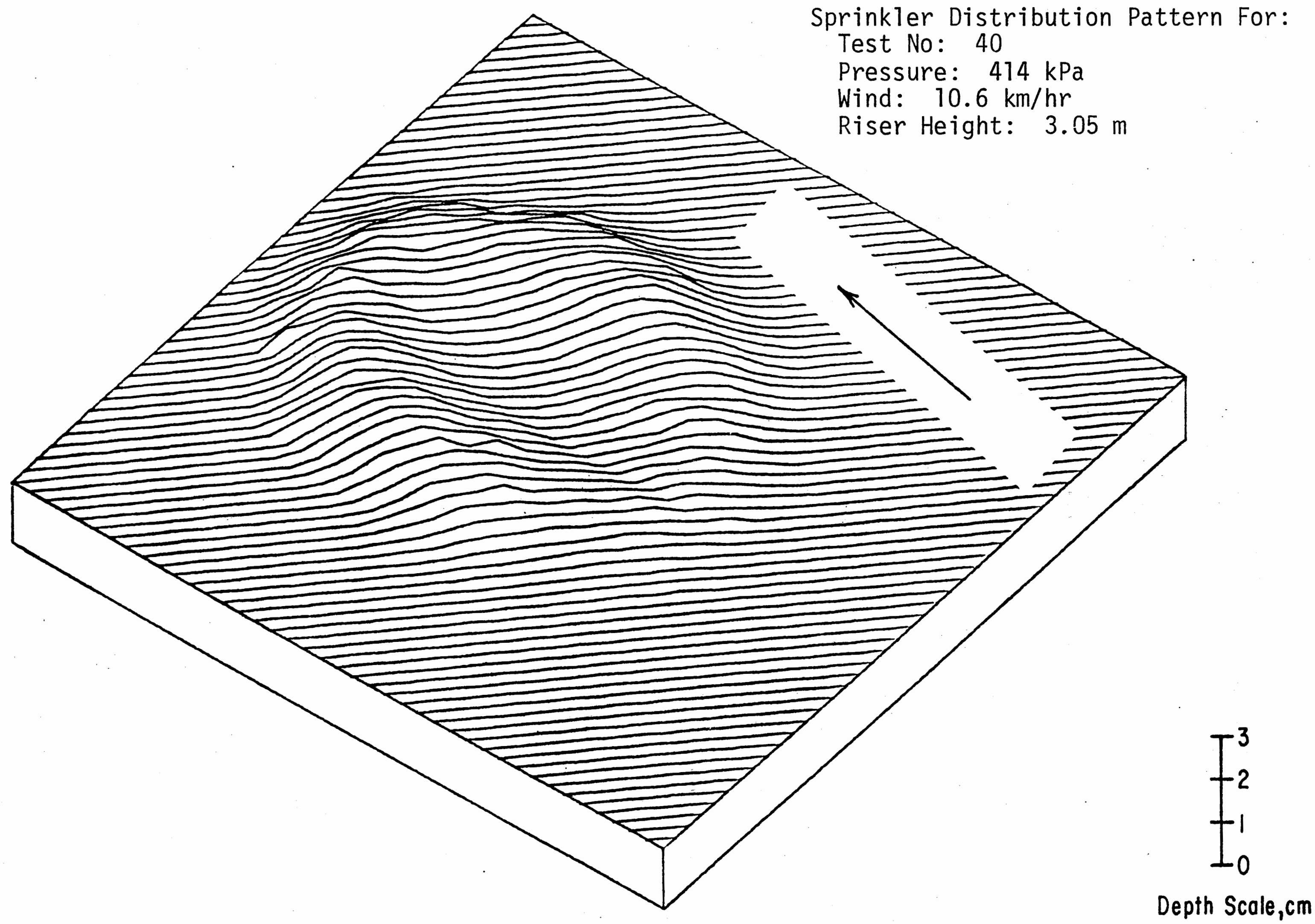
Depth Scale,cm

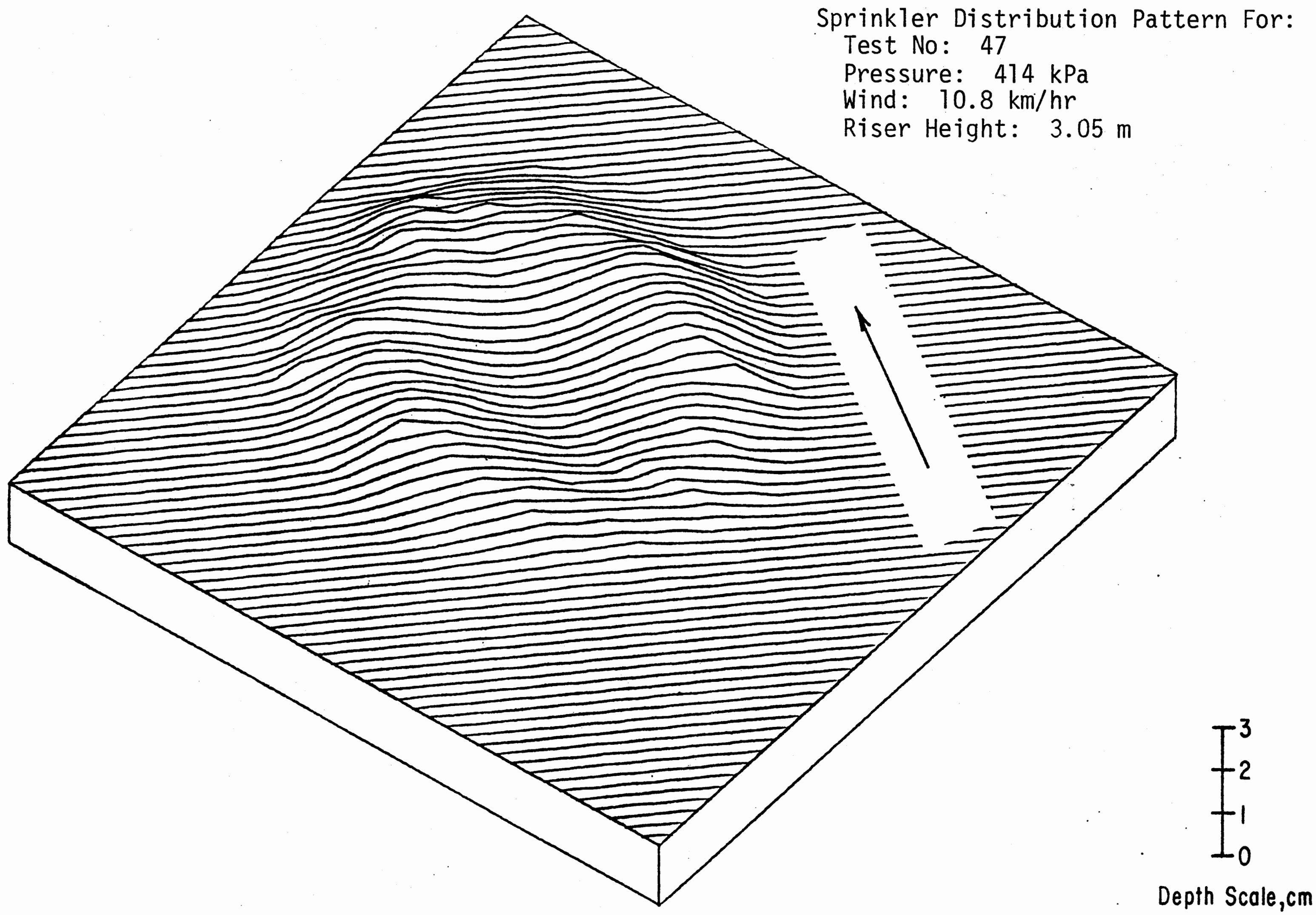

Sprinkler Distribution Pattern For:
Test No: 38
Pressure: 276 kPa
Wind: 10.9 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm

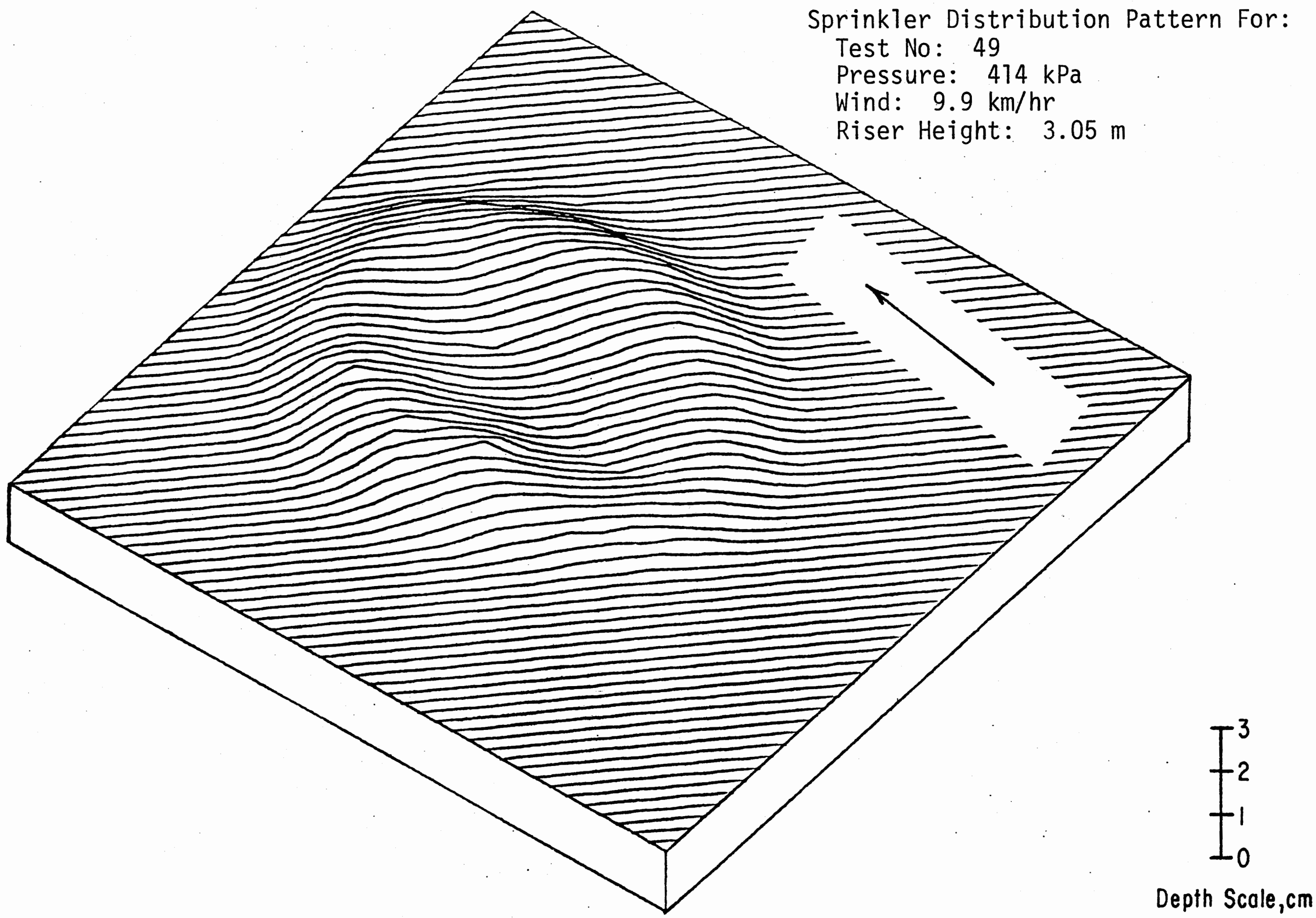
Sprinkler Distribution Pattern For:
Test No: 42
Pressure: 276 kPa
Wind: 10.6 km/hr
Riser Height: 3.05 m




Sprinkler Distribution Pattern For:
Test No: 46
Pressure: 276 kPa
Wind: 12.2 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm


Sprinkler Distribution Pattern For:
Test No: 40
Pressure: 414 kPa
Wind: 10.6 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm


Sprinkler Distribution Pattern For:
Test No: 47
Pressure: 414 kPa
Wind: 10.8 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm


Sprinkler Distribution Pattern For:
Test No: 49
Pressure: 414 kPa
Wind: 9.9 km/hr
Riser Height: 3.05 m
3
2
1
0
Depth Scale,cm

2

VITA

Sk. Md. Arshad Ali

Candidate for the Degree of

Doctor of Philosophy

Thesis: LOSS AND UNIFORMITY OF LOW TRAJECTORY CENTER-PIVOT SPRINKLERS

Major Field: Agricultural Engineering

Biographical:

Personal Data: Born in Khulna, Bangladesh, June 28, 1942, son of Mr. and Mrs. Toraf Ali; married to Selina Akhtar in 1968; son, Sheikh Manzoor Arshad, born in Dacca, Bangaldesh, September 25, 1974.

Education: Graduated from Khulna Zilla School, Khulna, Bangladesh, in 1960; completed higher secondary education from B. L. College, Khulna, Bangladesh in 1962; received the Bachelor of Science in Civil Engineering degree from Bangladesh University of Engineering and Technology, Dacca, Bangladesh, in 1966; received the degree of Master of Science in Agricultural Engineering from Oklahoma State University, Stillwater, Oklahoma, in 1977; completed the requirements for the Doctor of Philosophy degree at Oklahoma State University in May, 1981.

Professional Experience: Employed as Supervision Engineer in a construction firm in Barisal and Dacca, Bangladesh, 1967-1968; served as Assistant Engineer in Bangladesh Water Development Board, 1968; joined as a member of the Faculty of Agricultural Engineering, Bangladesh Agricultural University, Mymensingh, Bangladesh, 1968-1975; worked as Graduate Research Assistant in the Agricultural Engineering Department, Oklahoma State University, 1976-1980.

Professional Organizations: Student member of the American Society of Agricultural Engineers.