

CROP RESPONSE TO SOIL WATER POTENTIAL
AND DRIP IRRIGATION SYSTEM DESIGN

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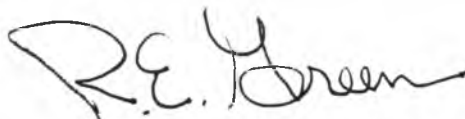
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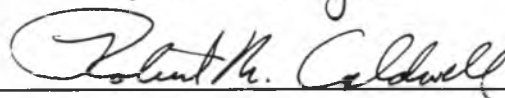
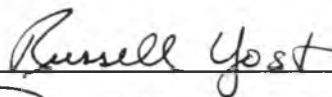
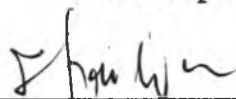
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ABSTRACT

Models of water movement for drip irrigation have been proposed as a means of incorporating soil hydraulic properties into the design of drip irrigation systems (Bresler, 1978; Warrick et.al., 1979). The crop component of these models has been represented by an arbitrary choice of the soil water potential at a point near the soil surface, midway between irrigation lines or emitters. The purpose of this research was to evaluate the use of the single midway soil water potential value or, alternatively, spatially integrated potential values in the root zone, by correlation with crop yield response. Another objective was to examine the adequacy of the Warrick model (1981) for prediction of wetting patterns.

The field experiment was conducted on a silty-clay (Typic Torrox) soil in Hawaii. Three treatments were subjected to different soil water potential distributions, which resulted from line-source spacings of 50, 100 and 150 cm. Sweet corn (*Zea mays* L.) was planted in rows spaced at 50 cm in all treatments. Soil water potential was measured at four depths and four distances from the line source using tensiometers and a pressure transducer. Three methods of integrating the soil water potential over space and time were used to calculate the representative values of soil water potential.

Results showed the impact of line source spacings on soil water potential distributions and crop yield. The soil water potential and crop yield decreased with increasing line source spacings. The integrated values of soil water potential using simple averaging and the Taylor (1952) method were highly correlated with crop yield, as compared to the Karamanos (1980) method. The single midway soil water potential and the representative value at the 15-cm depth were well correlated with crop yield, suggesting that this simple representation of crop water requirement may be useful in practical irrigation system design. The integrated values of soil water potential over all depths and over time also correlated well with crop yield.

The Warrick model predicted narrower ranges of soil water potential variation in comparison with field-measured potentials. Even so the model represented soil water potential distributions sufficiently well to be useful in drip irrigation system design.

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1. INTRODUCTION

The use of drip (trickle) irrigation systems has become a common practice in irrigation of many crops in recent years. The method is a fast-growing irrigation technology in agriculture and has been adapted to several types of crop production all over the world. A good drip system should provide application uniformity to satisfy water requirements of the crop. Any design must consider the wetting pattern to create the optimum moisture environment in the root zone without wasting water. Generally, emitters can be divided into two categories based on field application : line-source and point-source (Ross et.al., 1980). The water distribution under drip irrigation, in which two- or three-dimensional flow occurs, may be different from those under other irrigation methods. The water distribution in the soil profile with drip irrigation is affected by the emitter spacing and discharge rate, as well as by water application intervals, root uptake and soil hydraulic properties (Brant, et.al., 1971; Bresler, 1977, 1978; and Levin et.al., 1979; Warrick et.al. 1979, 1981; Schwartzman and Zur, 1986).

For row crops, usually the aim is to uniformly wet the plant row, which necessitates overlap of the wetted zones of each emitter (Dasberg and Bresler, 1985). Thus, the distance between emitters along the lateral and between laterals must be adapted to meet crop requirements. When the emitters are sufficiently close, then the water flow can

be analyzed as for a line source, which is usually used for closely spaced row crops. The design and operation of drip systems should integrate the plant, soil and system parameters. According to Bresler (1978) the main problem in drip irrigation design is selection of the proper combination of emitter spacing and discharge rate for a given set of soil, crop and climatic conditions. This selection requires knowledge of the crop response to size and form of the wetted soil volume, and to water distribution and fluctuation within the root zone. Bresler developed a procedure to estimate the spacing between emitters, including the effects of soil hydraulic properties and discharge rate. But the effect on crop growth of soil water potential between emitters (the allowable level of water depletion at the driest, critical plane midway between emitters) was selected arbitrarily for use in the design. A similar approach was presented by Warrick, et.al. (1979, 1980) and by Warrick and Lomen (1981, 1983) to include a sink term for plant water uptake in linearized water flow equations. The theory for linearized water flow from point or line sources with or without root water uptake and associated computer programs were developed by Warrick et.al. (1981). Improved two-dimensional solutions are also available to simulate different root water uptake patterns, along with soil water potential (pressure head) distribution patterns.

Many studies have shown that crop yield is strongly related to energy status of water thus to the soil water potential. Its single value has also been used (as a soil parameter related to crop response) for drip irrigation system design, as proposed by Bresler (1978) and Warrick, et.al. (1979, 1981), but field tests are needed. Soil water models to be used in drip irrigation system design should include the impact of water distribution in the soil on crop behavior, and conversely, the effect of the crop on soil water distribution. The adequacy of a single soil water potential value midway between emitters or emitter lines, as used in the models of both Bresler and Warrick, needs to be evaluated in view of the spatial and temporal distribution of soil water potential in the root zone. The soil water potential at a given depth and lateral position in the root zone may correlate well with crop response and provide a useful basis for irrigation. However, a single value of soil water potential measured at a given location and time may or may not be adequate to represent the critical point of crop water requirement due to the fact that water content in the root zone varies in both space and time throughout the crop growing season. This may require some means for integrating the soil water potential over time and throughout the entire root zone.

This study, therefore, aimed to evaluate the use of the midway soil water potential (h_c) to represent crop water

requirement in drip irrigation system design. Alternative representations of integrated or averaged soil water potential in the root zone were also assessed by a field experiment. Additionally, a mathematical model of water flow under drip irrigation (Warrick et.al., 1981) was evaluated by comparing predicted wetting patterns (soil water potential distribution patterns) with patterns measured under sweet corn in the field study.

OBJECTIVES:

1. Evaluate methods of integrating over space and time the soil water potential in the root zone of a row crop.
2. Evaluate the mathematical model of Warrick et.al. (1981) as a means of incorporating soil, crop and irrigation system parameters in simulating soil water potential distribution patterns under drip irrigation.
3. Evaluate the adequacy of a single midway soil water potential used in the models of Warrick, et.al. (1979) and Bresler (1978) to represent the crop water requirement in soil-water models used for drip irrigation system design.

2. LITERATURE REVIEW

2.1 Status of Research

In recent years, there have been a large number of studies on drip irrigation, but there have been very few studies of soil water movement under drip irrigation systems, or of system design in relation to soil hydraulic properties and crop water requirements. Much of the development in terms of system designs has been empirical; few recommendations have come from research studies. Also soil water models are often not applicable to drip irrigation design since they rest on a number of assumptions unlikely to be met in nature (Jury and Earl, 1977).

Bresler (1978) presented a theoretical analysis of drip irrigation design based on soil hydraulic properties and analytical solutions to two- and three- dimensional infiltration from a shallow pond (point source) developed by Wooding (1968). Bresler's approach provides a means of determining an appropriate combination of emitter spacing and discharge rate for soils with different hydraulic properties and different specified values of soil water pressure head at the midpoint between emitters. Application of this procedure was demonstrated on some Hawaii soils by Phalke, et.al. (1987).

Solutions to two- and three-dimensional linearized moisture flow with water extraction under drip irrigation were given by Warrick, et.al. (1979,1980,1981) and Warrick

and Lomen (1981,1983). These models can be used to simulate soil water potential distribution with or without root water uptake. As an aid for design and operation, Warrick, et.al. (1979) presented an algebraic equation to approximate the soil water pressure head at the midpoint between sources under steady state conditions, with or without plant uptake. This form allows straight-forward determination of soil water pressure head midway between sources using a calculator. In addition, nomographs relating pressure head midway between sources to rooting depth, source strength and uptake amount were developed as a further aid for the design of emitter spacing and discharge. Recent nomographs for drip irrigation system designs were also developed by Amoozegar-Fard, et.al. (1984). In addition, a method for determining width and depth of the wetted soil volume under the line and point sources was developed by Schwartzman and Zur (1987). Similarities of these models include assumptions that the geometry of the wetted soil volume is influenced by the hydraulic properties of the soil, emitter discharge, and the total amount of water in the wetted soil volume.

Russo (1983,1984) presented a geostatistical approach to drip irrigation system design in heterogeneous soils, based on Bresler's approach (1978), to evaluate the effects of spatial variability of soil hydraulic parameters and the midway soil water pressure head, under uniform and

non-uniform emitter spacing, on crop yield. Effects of drip irrigation design and management on crop yields have been reported by many researchers (Earl and Jury, 1977; Phene and Beale, 1976,1979; Singh and Singh, 1978; Kramer, 1980; Wu, 1982; Oron, 1984; Sammis and Wu, 1985; Wierenga and Saddiq, 1985). Knowledge of the relationship between soil water potential distribution and crop yield is still needed for effective drip irrigation. With a drip system, it is relatively easy to keep soil water potential at a given position at any specified level. However, little is known about the optimum level of water in the soil for drip irrigated crops (Wierenga and Saddiq, 1985).

2.2 Soil Water Movement under Drip Irrigation Systems

The movement of water into the soil under a drip emitter occurs in all directions in response to capillary attraction and downward as a result of gravity. Therefore, the distribution of irrigation water from a drip emitter is dominated by the physical properties of soils (Clothier, et.al., 1985; Dasberg and Bresler, 1985). The governing principles of soil water modeling for drip irrigation systems are the same as for other irrigation methods. The differences which exist are primarily in the geometry of the sources and the frequency of water applications. Moreover, only some parts of the total soil surface are wetted under

drip irrigation, and flow patterns vary vertically as well as laterally (Bucks, et.al., 1982).

2.3 Soil Water Flow Models for Drip Irrigation System Design

Mathematical modeling of soil moisture flow regimes for drip irrigation systems is, generally, based on Richards' equation, which combines Darcy's law with the continuity equation, subject to appropriate initial and boundary conditions and designated source and sink terms. The solution is difficult, in general, because of nonlinearity. Also, the two- and three-dimensional geometries of drip systems are more complex than one-dimensional cases typical for many other soil water regimes.

Solutions for transient and steady infiltration from point, line, strip and disk sources, which can be applied to simulate drip irrigation, have been published (Wooding, 1968; Raats, 1971; Philip, 1974; Warrick, 1974; Warrick and Lomen, 1974, 1976, 1981, 1983; Warrick, et.al., 1979, 1980). But there have been few comparisons between mathematical modeling results and experimental data.

The solution based on Wooding's theory (1968) has been used by Bresler (1978) in analyzing drip irrigation design problems. Using the Bresler method, Phalke (1987) found that for Oxisols tested in Hawaii with saturated hydraulic conductivities of 0.5 to 10.8 cm/hour, calculated emitter spacing varied between 9 and 70 cm for a discharge rate of

2.0 liters/hour, where the midway soil water pressure head was assumed to be -40 cm of water. Bresler (1978) suggested that large spacings are permitted in soils with relatively low values of hydraulic conductivity and alpha parameter, and also when the crop grown is not sensitive to water stress or to partial soil wetting (lower value of pressure head at the midway between emitters, h_c , is permitted). Smaller spacing is required for soils having higher hydraulic conductivity and alpha value and when sensitive crops are being grown.

Warrick, et.al. (1979) solved the linearized water flow equation for two-dimensional line sources (buried or on the surface) with one-dimensional water extraction. Computer programs for the linearized solutions to two- or three-dimensional flow from a point or a line source with or without plant uptake were also presented by Warrick, et.al. (1981). The linearization is attained in a steady state case by assuming that unsaturated hydraulic conductivity, K , is exponentially related to the pressure head, h , i.e. $K = K_0 \exp(\alpha h)$, where K_0 and α are empirical constants. They also used a Kirchhoff integral transformation and defined a matric flux potential, ϕ , after Gardner (1958) by

$$\phi = \int_{-\infty}^h K(h) dh$$

Using a conductivity of this form, the differential equation based on Richards' equation becomes

$$\frac{\partial \theta}{\partial t} = \nabla^2 \phi - \alpha \frac{\partial \phi}{\partial z} - S$$

where S is the uptake rate or a sink function which is simply added to the flow equation, and ∇ is the Laplacian operator. For the steady state situation, $\partial \theta / \partial t$ is zero, resulting in

$$\nabla^2 \phi - \alpha \frac{\partial \phi}{\partial z} - S = 0$$

The time dependent cases can also be derived by assuming $dK/d\theta = k$ which is constant. The result is

$$\frac{\partial \phi}{\partial t} = (k/\alpha) \nabla^2 \phi - k \frac{\partial \phi}{\partial z} - (k/\alpha) S$$

In addition, an algebraic formula was developed to approximate the value of soil water pressure head midway between sources. This equation is, however, only valid for steady state conditions with no surface loss and a uniform uptake function. Simulated results indicated that this value was lower (more negative) with plant uptake than without plant uptake. Based on the same assumptions, Warrick, et.al. (1980) presented solutions to three-dimensional linearized moisture w with cylindrical root

extraction, which is assumed to be uniform over the cylinder. They also proposed two-dimensional linearized moisture flow with two different patterns of root extractions: 1) plant uptake decreases exponentially with depth and with lateral distance (Warrick and Lomen, 1981), and 2) the plant uptake pattern is represented as a series of rectangular regions, each of which has an explicit uniform uptake (Warrick and Lomen, 1983).

Recently, Amoozegar-Fard, et.al. (1984) developed a series of nomographs for drip systems of line, point and disk sources, buried or at the surface, to aid the potential user by avoiding having to sort through the publications or perform specific computations. In developing the nomographs for the design and operation of drip systems, they related plant uptake characteristics, rooting geometry and uptake rate, water application rates, and soil properties to the soil moisture status at a reference location within the soil profile.

2.4 Determination of Crop Water Requirements

Knowledge of crop water requirements, often called consumptive use or evapotranspiration (ET), is necessary in irrigation planning and proper timing of irrigation. Its value varies with climatic conditions and the growth stage of the crop, as well as with the type of crop.

There are several methods for measuring or estimating actual evapotranspiration, potential (reference) evapotranspiration and crop coefficients of various crops. Detailed information is given by Jensen (1973, 1980); Doorenbos and Pruitt (1977); Burmann, et.al. (1980); Pruitt, et.al. (1984); Phene, et.al. (1985); and many other researchers.

Chang et.al. (1965) reported that the Penman equation gave estimates of potential evapotranspiration of sugarcane in Hawaii which were about 18% less than evaporation from a Class A pan. Correlation between the two methods, however, was relatively good. Ekern (1977) found that estimation of potential evapotranspiration from net radiation underestimated lysimeter use, probably due to significant absorption of advection heat by the cane canopy. Jones (1980) concluded that in Hawaii, pan evaporation gives an adequate estimate of potential evapotranspiration of sugarcane only when long-time (monthly) averages are used.

McGillivray et.al. (1985) described ET field studies and outlined a method for estimating current crop ET using current pan evaporation data (E_p) and empirically derived relationships (K_p) between crop ET and measured E_p . They evaluated the reliability and use of current ET estimates to guide irrigation scheduling for tree and vine crops under drip irrigation. Yields of these crops increased with

irrigations carefully applied in accordance with estimated crop water use.

Phene and Campbell (1975) developed automated pan evaporation measurements for irrigation control, and concluded that Class A pan evaporation measurements are reasonable estimates of evapotranspiration in humid climates when soil water is not restricting plant growth. If suitable pan factors are available (Doorenbos and Pruitt, 1977), an open-water surface-evaporation measurement instrument can be used to control automatically an irrigation system.

Soil moisture measurements have also been used widely to quantify and control irrigation scheduling, as reported by Campbell and Campbell (1982), Pogue and Pooley (1985), and Lavin et.al. (1985). Moreover, methods of estimating crop water requirements using evapotranspiration combined with soil moisture status or soil moisture potential have the advantage of not only being useful in determining when to irrigate, but also in specifying the quantity of water needed (Goyal and Rivers, 1985).

2.5 Soil Water Potential and Crop Response to Drip Irrigation

Soil water potential plays an important role in water flow theory, as well as in plant water relations. Water potential is highest in the soil, and decreases along the transpiration path. This potential gradient provides the

driving force for water transport from the soil to the atmosphere (Campbell, 1985). Campbell concluded that reduction in soil water potential decreases plant water potential, closes stomata, and decreases transpiration and crop production.

Crop response to water can be related to soil water conditions when an estimate of soil water potential is averaged over the zone of water extraction (Karamanos, 1980). A simple averaging of soil water potential at different depths is likely to lead to misleading results (Hunter and Kelly, 1964; Slavikove, 1967). A single value of soil water potential has been used in several models of water uptake by plant roots (Gardner, 1964; Herkelrath, et.al., 1977; Hillel, et.al., 1976; Rowse, et.al., 1978). Soil water potential measurements by tensiometers are also frequently used for irrigation scheduling practices.

Studies of crop response to water applications indicate that production of many crops is increased by maintaining the water regime at high average values of soil water potential over time in the effective root zone. Although it is virtually impossible to grow plants under conditions of constant soil water potential or soil suction (Gardner, 1964), with drip irrigation it is relatively easy to keep the soil water potential near an optimal level.

Phene and Beale (1976) conducted an experiment on sweet corn with high-frequency irrigation for water and nutrient

management in humid regions. Results showed that the marketable ear yields of sweet corn did not differ among plots irrigated at -100 cm, -200 cm and -400 cm matric potential levels with fertilizer applications were kept at the same rates, possibly because high-frequency irrigation tends to apply water often to wet small portion of the root zone. However, they concluded that optimal ear yield on sandy soil was produced with high-frequency trickle irrigation when the soil matric potential at 15 cm soil depth was controlled at about -200 cm of water. Another experiment was conducted by Phene and Beale (1979) to determine the influence of twin-row spacing versus conventional row spacing with the same plant population. A single trickle irrigation tube was placed between twin rows, and one tube was used for each row of conventional spacing. Minimal soil matric potential was maintained between -200 and -250 cm (optimal range) during the growing period. Results showed that the twin-row planting which required 40 % less tube than conventional row spacing did not detrimentally affect yield, biomass production, N uptake and water-use efficiency of sweet corn. The means of measured soil water potentials over the growing season were not significantly different between the two spacings. Arya et.al. (1975) reported that soil water potentials in the root zone of soybean during the irrigation drying cycle were marked by strong lateral and vertical gradients, especially

during the early growth period; as plants aged, these gradients decreased.

A study to determine relationships between soil water potential and yield and quality of chile peppers was conducted by Wierenga and Saddig (1985). They found that the optimal range of soil water potential for trickle irrigated chile peppers grown on clay loam soil was between -150 and -250 cm. The soil water potentials were averaged over all depths (15, 30 and 50 cm) for each treatment over the growing season. When the average soil water potential values were higher or lower than this range (-150 to -250 cm), yield started to decrease.

Wolff (1985) demonstrated that the highest yields of tomatoes, head lettuce, and radishes under drip irrigation were obtained at soil water potentials between -60 and -140 cm of water. Decreased yields were recorded for lower (more negative) soil water potentials. Results from the study of drip irrigated sweet corn conducted in Arizona by Doerge et.al., (1989) show that there was no difference in total weight of ears between treatments receiving water applied at rates of 1.0 and 1.3 times the consumptive use. however, the total weight of ears produced from the treatment with a rate of 0.7 consumptive use was significantly lower than those of the other two treatments. They also found that higher water application rates generally had less effect on yield and quality of sweet corn than did nitrogen rates.

The maximum marketable ear yield obtained in this study was 3.1 ton per hectare, using nitrogen at the rate of 182 kg per hectare and 53.6 cm of irrigation water. Stroehlein et.al. (1988) conducted a field experiment in Arizona, they found that consumptive use of the drip irrigated sweet corn planted in March, 1987 was about 49.8 cm. Increasing water from low- to mid- rates (40.1 to 60.9 cm) improved all yield parameters of sweet corn in general. A significant difference in yield resulted from the high rate of water (72.4 cm), but the differences were numerically much less than the differences between the low- and mid- water rates. The crop response curve studied by Wu (1982) showed a steep rise in yields of chinese cabbage and lettuce with increasing water application under drip irrigation, and a decreasing rate of crop yield increase for further increases in water application. Sammis and Wu (1985) concluded that average yield over a large drip irrigated field is affected by application uniformity, amount of water application, amount of rainfall and crop sensitivity to moisture stress conditions. A non-uniform soil water potential may result in a non-uniform crop yield throughout the field, which, in turn, may cause a reduction in the average crop yield. Studies of Russo (1983,1984) using Bresler's (1978) approach demonstrated that the concept of optimal soil water potential at midpoint between emitters (h_c) is relevant during early stages of crop growth, when the root system is

not fully developed. Both theoretical and experimental results showed that although soil hydraulic parameters (K and α), as well as h_c , varied considerably in the field, the spatial variability of the crop yield was relatively small. The use of a spatially variable spacing between emitters (d) reduced the dependence of yield on h_c . This indicates that when the emitters are properly spaced, it is not the water but other factors that most influence the crop yield.

2.6 Representative Values of Soil Water Potential and Crop Yield

Although the soil water potential at a given depth in the root zone may correlate well with crop response and provide a useful basis for irrigation, integrating the soil water over the entire root zone may still be needed in order to have a clearer understanding of how crop responds to water conditions in the root zone. Gardner (1964) stated that crop response to water can be related to soil water conditions when an estimate of soil water potential averaged over the zone of soil water extraction is available. Many attempts have been made to relate crop response to an integrated soil water potential value (Taylor, 1952) and good correlations have been reported between this integrated value, crop growth and yield (Denmead and Shaw, 1962; Arya, 1975; Wierenga and Saddiq, 1985).

The difficulties in calculating such an integrated soil water potential mainly arise from the non-uniformity of root

density within the soil profile affecting water distribution, as well as from the variation in root resistance to water flow from the different layers of the root system (Taylor and Klepper, 1975). Gardner (1964) suggested a method based on theoretical considerations of the movement of soil water towards roots and calculating an integrated value by weighing the values of soil water potential at different depths according to the root density and unsaturated soil conductivity at each depth. Some studies indicated that simple spatial averaging of soil water potential may be inadequate (Bormann, 1957; Slavikova, 1967) because a sample averaging of soil water potential at different depths is likely to lead to misleading results.

Taylor (1952) developed a method of integrating soil water potential over depth and time. This method involved fitting polynomial regressions to values of soil water potential from field data over depth and time, then combining the two regressions and using a double integral to give an average soil water potential for the root zone over a specified time interval. Theoretically, soil water potential (T) is a continuous function of both depth and time, which can be expressed as:

$$T = f(x,t) \quad (1)$$

where x represents depth below the soil surface and t represents time. The relationship of soil water potential

and depth at any given time can be expressed the soil water potential as a polynomial in x at time i by the equation

$$T_i = f(x) = a_0 + a_1x + a_2x^2 + \dots + a_nx^n \quad (2)$$

where a_1, a_2, \dots, a_n are time dependent parameters. The soil water potential at a given depth during the cycle between irrigation applications T_j can be represented by a functional relationship of the kind

$$T_j = f(t) = b_{0j} + b_{1j}t + b_{2j}t^2 + \dots + b_{kj}t^k \quad (3)$$

where $b_{0j}, b_{1j}, b_{2j}, \dots, b_{kj}$ are the depth-dependent parameters. Equations (2) and (3) can be combined to give a general functional relationship. The soil water potential at any given depth and any given time is then,

$$T_{ij} = P_0(t) + P_1(t)x + \dots + P_n(t)x^n \quad (4)$$

where $P_0(t), \dots, P_n(t)$ represent polynomials in time, t .

The integrated soil water potential (Tr) in the root zone is then the double integral of equation (4) for both depth and time and can be represented by the equation

$$Tr = \int_{t_0}^{t_1} \int_{x=d_0}^{x=d} T_{ij} dx dt$$

where d_0 is the depth at the soil surface and d is the depth of the root zone, t_0 is the beginning time of the chosen interval, which may be the growing season, and t_1 is the end of the time interval. Taylor claimed that this method is adequate for many applications.

Another method was developed by Karamanos (1980), where soil water potential values from individual soil layers were

weighted according to the rate of soil water depletion in a soil layer at the measurement. Soil water depletion was determined for periods between two samplings and the rate of depletion at a particular sampling was taken as the average depletion for two successive time intervals.

2.7 Root system development under drip irrigation

The distribution of roots affects soil water potential and water extraction patterns in the root zone (Gardner, 1964; Van Bavel, 1968; Molz, 1971; Rice, 1975; Arya, et.al., 1975; Lascano and van Bavel, 1984). Many models have been developed recently to determine water uptake by plants, as reviewed by Molz (1981) and Alaerts, et.al. (1985).

Knowledge of rooting characteristics can be used to explain crop response to irrigation. This is particularly true when considering crop response to drip irrigation. If drip systems are to be designed and managed well, it is necessary to know how the growth and extent of root systems are affected by different conditions. It is recognized that distribution of roots under drip irrigation is restricted to the wetted volume of soil beneath each emitter (Bernstein, et.al., 1973; Bucks, et.al., 1974; Levin, et.al., 1979), with root density decreasing with lateral and vertical distance from the emitter (Jury and Earl, 1977).

A study of root development of drip irrigated sugarcane showed more root growth toward areas of higher soil water

potential around the drip lines (Batchelor et.al., 1985). Amoud and Kay (1985) described techniques used to monitor the growth and distribution of root systems under drip irrigation with a wide range of water application rates and intervals. They found that in all treatments more than 60% of the active roots of a tomato crop grown in a sandy loam soil were observed in the top 30 cm of the soil profile, and that 90% were contained within a 50 cm depth of soil. Shani (1985) concluded that water content distribution under drip irrigation seems to have a major effect on root growth. Results from his experiments on bell-pepper, cotton and melon with minimized interaction between adjacent drippers, showed a peak in root density at some radial distance from the symmetrical axis of the wetted volume, with a decline toward the center (because of aeration shortage in the higher water content zone beneath the dripper), and a decline in root density at further distances resulting from low water potential.

3. MATERIALS AND METHODS

3.1 Field Experiment

3.1.1 Design and Execution

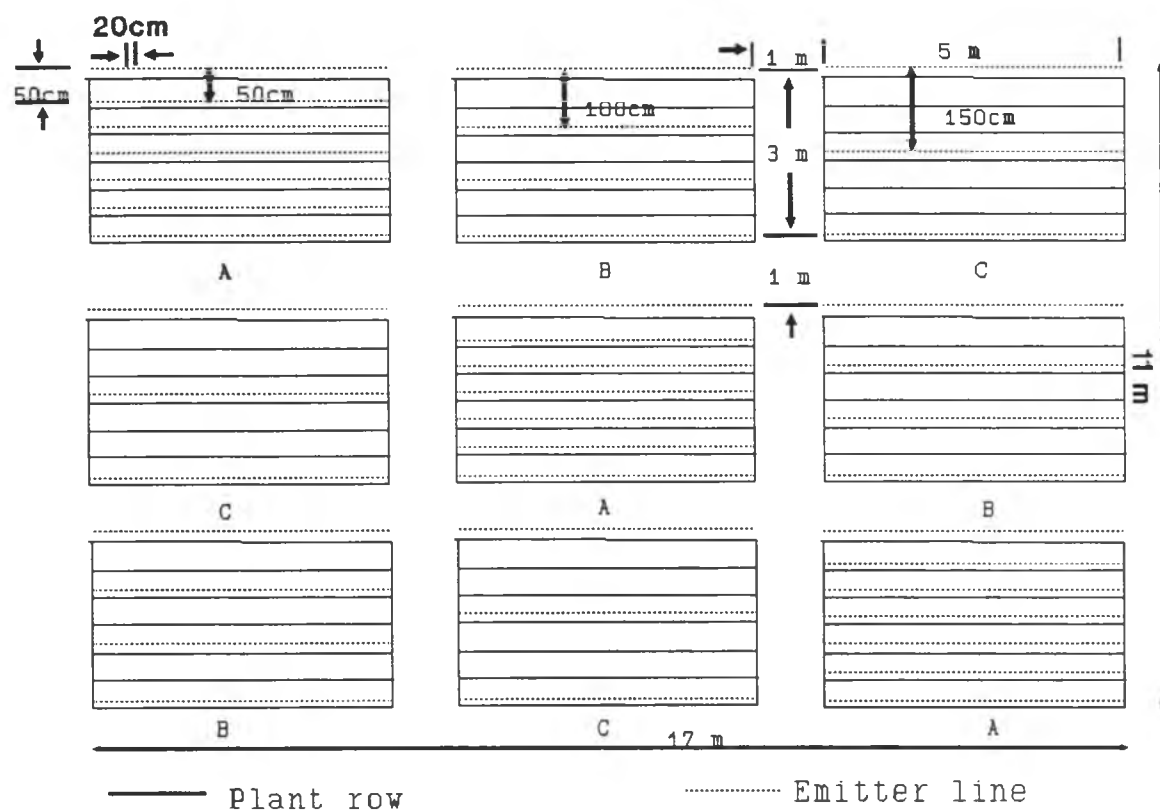
The purpose of this experiment was to evaluate the utility of a single value of soil water potential and other representations of soil water potential distribution within the root zone, in relation to crop response under different spacings of line sources. The experiment also provided data to evaluate the applicabilities of the linearized water flow model used in drip irrigation system.

The experiment was conducted at Hawaii Sugar Planters' Association (HSPA) Substation at Kunia. The soil is classified as Typic Torrox (Molokai Series). An area with relatively uniform soil was selected for the experiment site. The soil was tilled to depths of 30 to 35 cm. A plow pan was evident at depths of approximately 35 to 40 cm.

Treatments consisted of three spacings of line sources (50, 100 and 150 cm) with three replications using a randomized complete block design (Figure 1a). In addition, continuous or systematic treatments (Figure 1b) were included to provide more information on the relationships between crop yield and soil water potential at different distances from emitters.

Sweet corn (*Zea mays* L., Hawaiian Super-sweet #10A) was planted in experimental plots on May 22, 1989. The size of each plot was 6 x 7.5 m with 20 cm spacing between plants

and 50 cm spacing between rows. Plants were thinned to the same population for each treatment (90,000 plants per hectare) with one stalk per plant.



Treatments: A = 50 cm spacing between lines
 B = 100 cm spacing between lines
 C = 150 cm spacing between lines

Plant spacing: 20 cm between plants
 50 cm between rows

Emitter spacing: 20 cm between emitters

Figure 1a Field layout of experimental treatments.

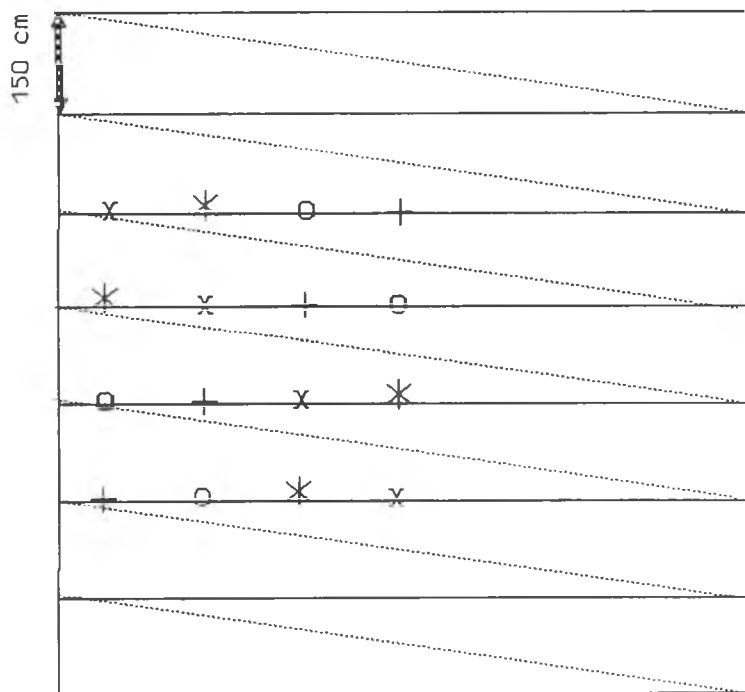
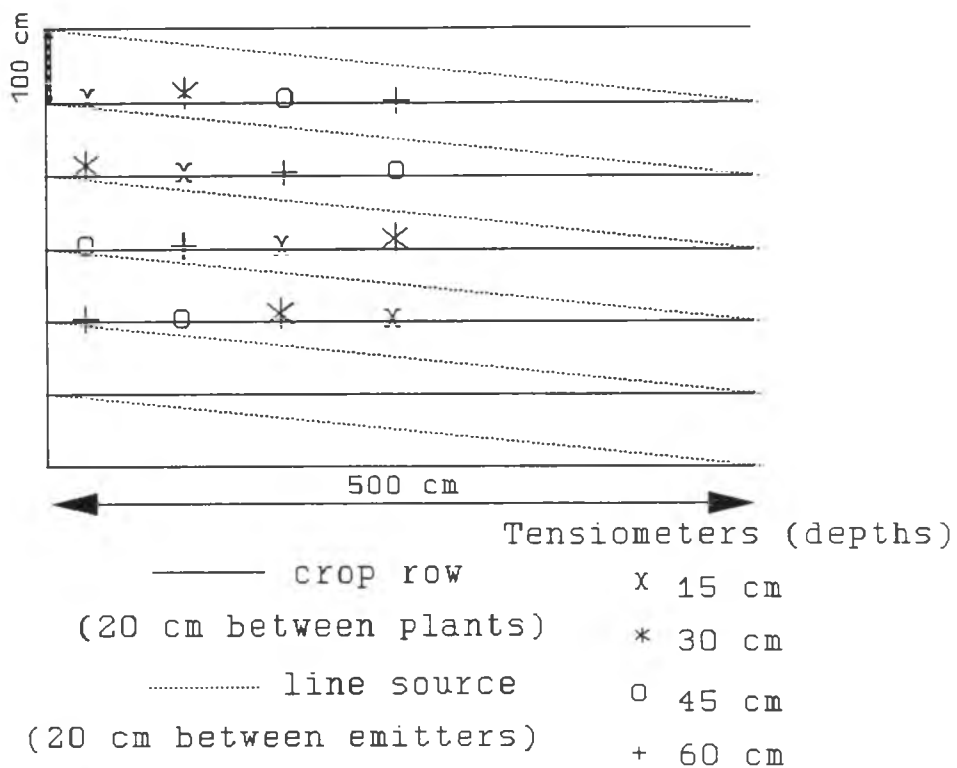


Figure 1b Supplementary treatments with different depths and distances of tensiometers from the drip line.

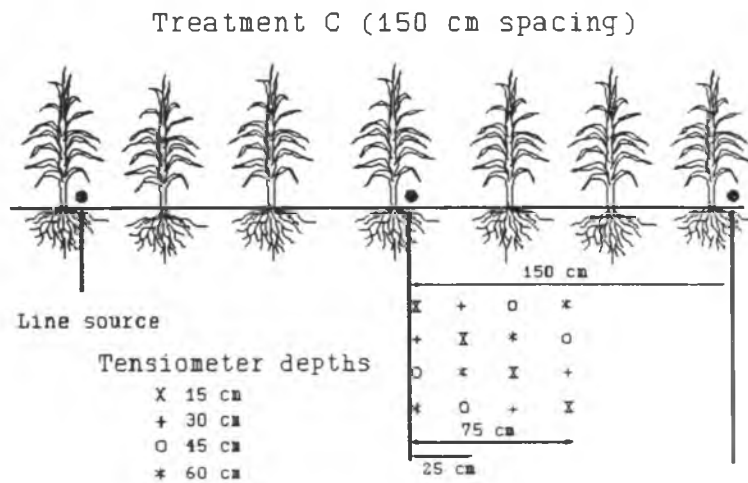
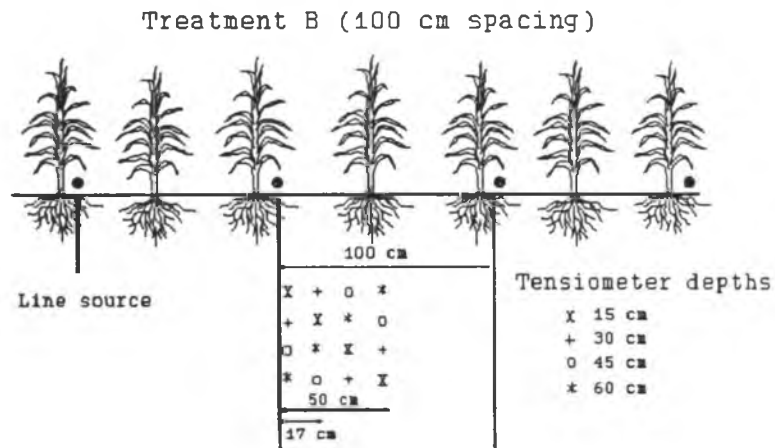
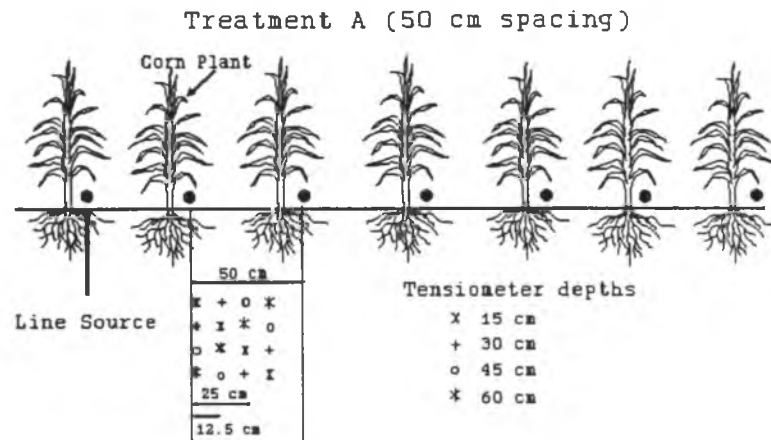


Figure 2a Locations of tensiometers at different depths and distances for treatments A, B and C.

Fertilizer of N-P-K (10-30-10) was broadcast uniformly at the rate of 280 kg per acre before planting. Additional fertilizers of urea and potassium chloride were applied as side dressing about three and six weeks after planting at 80 and 55 kg per acre. Weed control was achieved by preemergence application of Atrazine (Attrex) and Alachlor (Lasso). The insecticides of Sevin and Malathion were applied when necessary during a period of vegetative growth.

Each treatment plot was equipped with a standard drip irrigation system using Turbo-tape (T-system) with 20 cm spacing between emitters. The operation pressure was 10 psi (pound per square inch) with a capacity of 16 gpm (gallon per minute). The emitter line sources were installed on the soil surface in accordance with the treatments defined, i.e. 50, 100 and 150 cm spacings.

The amount of irrigation water applied was quantitatively adjusted according to the amount determined with a Class A evaporation pan, the amount of rain and the physiological age of the crop. Thus, the amount of water applied varied according to stages of crop development and the potential evapotranspiration that was estimated from a Class A pan measurement. The field was irrigated daily for three weeks to enhance the germination and early growth, and later at four day intervals. All treatments received the same amount of irrigation water per unit area controlled with automatic metering valves.

To measure soil water potential, tensiometers were installed in two dimensions, i.e. 15 cm vertical intervals to 60 cm depth of the root zone and at various horizontal intervals to the midpoint between line sources of each treatment (Figure 2). Additional tensiometers were also installed near the surface (about 5 cm depth) at the midpoint between line sources.

3.1.2 Data Collection and Measurements

3.1.2.1 Weather Data : The weather data were obtained from the weather station located near the experimental site. These data included rainfall, temperature, humidity and wind. Pan evaporation data were collected and used in combination with the rainfall data to estimate the amount of irrigation water.

3.1.2.2 Soil Data : Soil water potential was measured in two dimensions using tensiometers along with a portable, hand-held pressure transducer (Tensimeter by Soil Management Systems, Tucson, Arizona). Tensiometer readings (millibar) were taken early in the morning before and after each irrigation at approximately the same time (Figure 2b). The tensimeter was calibrated with a laboratory manometer and the data were converted from the volume to the weight basis. As a supplement to the tensiometer data, soil samples were obtained from the surface to 60 cm depth for gravimetric water content determination. This was done periodically according to the stages of crop development. Soil hydraulic

properties, particularly hydraulic conductivity (K) and α parameter, were obtained from field measurements under the project 'Matching drip irrigation system design and operation to soil hydraulic properties'. Published soil parameters for Molokai series (from areas nearby the experimental site) were also available (Green et.al., 1982; Bresler and Green, 1982).

3.1.2.3 Crop Data : Growth and development of the sweet corn crop were analyzed at regular time intervals according to crop growth stages. According to the literature, the crop growing season was divided into four growth periods (Figure 2b):

1. Initial stage - 1 to 20 days after planting (ground cover <10%).

2. Crop development stage - 21 to 40 days after planting (vegetative development, ground cover about 70 - 80%).

3. Mid-season stage - 40 to 60 days after planting (reproductive development, tasseling and silking, full ground cover to time of maturity).

4. Late-season stage - 60 to 75 days after planting (full maturity or harvest).

The crop data included plant height, leaf area index (LAI) and rooting depth at different growth stages. Rooting depth was measured by excavation method. Yield response, including number, weight and length of marketable ears, and

3.1.3 Data analyses

3.1.3.1 Data input and simple calculations were done using a spread sheet program (LOTUS 1-2-3).

3.1.3.2 Statistical analyses were performed on soil water potential data and crop yield data, using SAS software (SAS Institute Inc., North Carolina).

3.1.4 Methods of Calculating a Representative Value of Soil Water Potential

The soil water potential data measured at different locations within the root zone throughout the growing season were used to examine three methods of computing representative soil water potential values for the root zone.

3.1.4.1 A simple averaging of soil water potential over depths and time of the crop growing season.

3.1.4.2 The method developed by Taylor (1952), involved fitting polynomial equations to values of soil water potential from field data over depth and time, then combining the two regression equations and using a double integral to give an averaged soil water potential for the root zone over a specified time interval.

3.1.4.3 A weighted soil water potential at a given time (Karamanos, 1980) was calculated from the following equation:

$$\bar{\Psi}_m = \frac{\sum_{z=1}^n \left(\frac{\Delta\theta}{\Delta t} \right)_z \Psi_{m,z}}{\sum_{z=1}^n \left(\frac{\Delta\theta}{\Delta t} \right)_z}$$

where $\Delta\theta/\Delta t$ = the rate of water depletion
 $\Psi_{m,z}$ = the soil water (matric) potential at a
depth z for the particular time
 n = the number of soil layers

Soil water depletion was determined for the period between two samplings, and the rate of depletion at a particular sampling was taken as the averaged depletion for two successive time intervals.

3.2 Relationships between Soil Water Potential and Crop Growth and Yield

The data of soil water potential (distribution patterns, a single value, h_c , a representative (integrated/averaged) value and values at different locations) were statistically related to crop growth and yield to evaluate how crop response related to soil water potential values. Statistical data analyses were performed. The correlation analyses of soil water potential and crop yield were as follows:

3.2.1 Soil water potential distribution and crop yield

3.2.2 Soil water potential at different depths and distances, and crop yield

3.2.3 A representative value of soil water potential (integrated/averaged values) and crop yield.

3.2.4 Soil water potential midway between line sources and crop yield.

3.3 Model Application

The mathematical model of linearized water flow from line source with root extraction (developed by Warrick et.al., 1979 and 1981) was used to simulate soil water pressure head distribution under drip irrigation (surface line sources) and plant uptake conditions.

The theoretical background is presented in the literature review. Linearized solutions to two- or three-dimensional flow problems were given for both steady-state and time-dependent flow, with or without root extraction. The solutions to two-dimensional flow were applied for this study, since a row crop and line sources with close spacing were under consideration. Computer programs were also provided in FORTRAN along with the manual to allow easy application of available solutions. The program for the two-dimensional flow problem was further modified (Dr.Warrick, February 1990) to be applicable with microcomputers using FORTRAN 5.0 (Microsoft Corporation). This program was used to demonstrate the applicability of the soil water flow model for drip irrigation. To compare with field data, the solutions to the steady-state case for two-dimensional flow with different water extraction patterns were emphasized and evaluated. Three different

patterns of water extraction or sink terms used in the model are as follows:

1. Water extraction is one-dimensional and uniform throughout for any given depth of the root zone.

2. Water extraction can be split into two to four fractions within the root zone depth; each fraction is one-dimensional and uniform.

3. Water extraction is two-dimensional (strip sink), defined in x and z dimensions within the root zone.

The data inputs required in the model were:

i.) Soil and system parameters

1. The α parameter (unit: length⁻¹)
2. The empirical constant, K_0 (unit: length/time)
3. The constant k , $dK/d\theta$ - assumed constant- used only for the time-dependent case (unit: length/time)
4. Number of x, z, t coordinates (t used only for time-dependent case)
5. Number of line sources
6. Spacing between lines (unit: length)
7. Strength of sources (unit: length²/time) based on the rate of water application and spacing between sources.

ii.) Crop parameters (strength of sink)

The strength of sink (rate of water extraction) was determined by the pan evaporation method which integrated the effect of radiation, wind, temperature and humidity on

evaporation from a specific open water surface (Doorenbos and Pruitt, 1977).

$$ET_o = K_p * E_{pan}$$

$$ET_{crop} = K_c * ET_o$$

where ET_o = the potential crop evapotranspiration
 K_p = pan coefficient
 E_{pan} = pan evaporation
 ET_{crop} = crop evapotranspiration (consumptive use)
 K_c = crop coefficient (recommended values)

The values of these parameters used in the computer program are given in Section 4.3.

3.4. Model Evaluation

The simulated results obtained from the model, using different patterns of root uptake for different growth stages and different spacings of line sources, were compared with experimental data to ascertain the reliability and applicability of the theoretical model. Soil water potential distribution obtained in the field and with the model were compared for different periods of growth.

3.5 The evaluation of a single value of soil water potential as related to crop response

The single value of soil water potential, either h_c or a computed representative (integrated/averaged) value, was examined to determine how well such a value could represent the critical point for crop water requirement used in drip irrigation system design.

4. RESULTS AND DISCUSSION

4.1 Field Experiment: Soil Water Potential in Space and Time

Soil water potential (SWP) was measured in drip irrigated sweet corn at four depths and four distances from emitter lines, using tensiometers and a hand-held pressure transducer with digital readout. The drip irrigation system used can be described as a line source as the emitters within the line are closely spaced (20 cm) to provide a nearly continuous strip of wetted soil along the row. To observe the effect of spacings of line sources on SWP distribution patterns, three spacings (50, 100, and 150 cm) of line sources were installed for this experiment. Tensiometers were also placed at midpoints between the line sources in all plots to evaluate the SWP at the midpoint between the lines where zones of dry soil usually occur. The tensiometer data were recorded before and after irrigation throughout the growing season. These data were analyzed to show variation in soil water potential with time at different vertical and lateral positions including the two dimensional distributions of SWP values within the main root zone.

It should be noted in this study that soil water potential (SWP), also called soil water pressure head, has a unit of negative cm of water (-cm), which is an expression of soil water energy on the weight basis. Numerically high negative values thus represent low SWP and low water

content. The results of SWP obtained from the field experiment were compared with the model results.

4.1.1 Variation in Soil Water Potential During Growing Season

Soil water potential (SWP) was measured before and after irrigation during the period June 14 to August 4, 1989 (Julian day 165 to 215) starting about three weeks after planting. Tensiometer readings were calibrated and converted from the volume basis (millibar) to the weight basis (-cm of water). Individual plot data were used to calculate means from three replications. The coefficient of variation (C.V.) of SWP among the three replications was computed for each treatment and depth and lateral position throughout the growing season. For example, the C.V., the mean and standard deviation were calculated for SWP values at 15 cm depth and position 1 (next to the drip line) of each treatment (Appendix A).

Changes in SWP versus time were plotted in Figure 3 for the 15, 30, 45 and 60 depths using the means of SWP at four distances from line sources. This figure shows the response in SWP resulting from different spacings of line sources for the same amount of water applied per unit area. The data show that ranges of the SWP were similar for all treatments at the time before the treatments started (142 Julian day). Soon after, changes in the SWP started to increase until the end of growing season. The most variation in SWP occurred

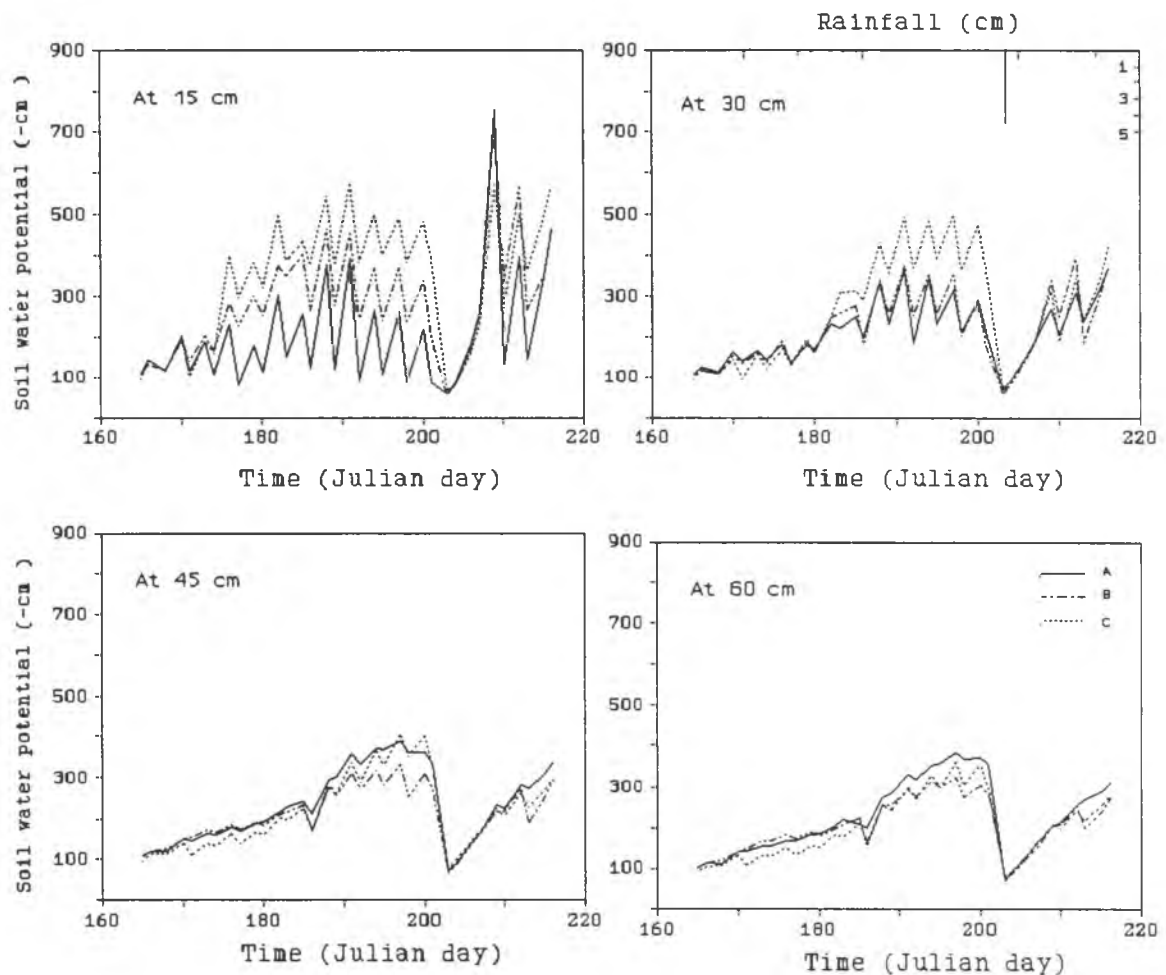


Figure 3 Variation in soil water potential versus time for 15, 30, 45 and 60 cm depths under 50, 100 and 150 cm spacings of line sources (Treatments A, B and C respectively).

near the surface and at 15 cm depth, probably because of drainage, surface evaporation and water extraction by plants. The differences in SWP among the three treatments were small for the 45 and 60 cm depths. And the soil in treatments B and C was wetter at these lower depths as

compared with the soil in Treatment A. Recall that the amount of water applied was the same per unit plot area for all treatments, but treatment B received two times as much water per unit length of drip line as treatment A, and treatment C received three times that of treatment A. This was due to different spacings of line sources among the three treatments. Thus there was much more deep penetration of water in treatments B and C.

There was more water distributed near the surface of treatment A, whereas there was more water distributed vertically below the line sources of treatments B and C, respectively. It should be noted that there was about 5 cm of rain on July 21 (day 202). The soil became uniformly wet and the SWP increased to nearly the same values for all treatments. The irrigation was then stopped for 7 days. When the irrigation cycle continued, the temporal variation in SWP for the three treatments showed similar patterns to what appeared previously.

Table 1 Lateral location of tensiometers in centimeters from the drip line for the three treatments*.

Treatment	Distance 1	Distance 2	Distance 3	Distance 4
A	0	12.5	25	37.5
B	0	17	34	50
C	0	25	50	75

* See Figure 2 in Methods for layout of tensiometer arrays.

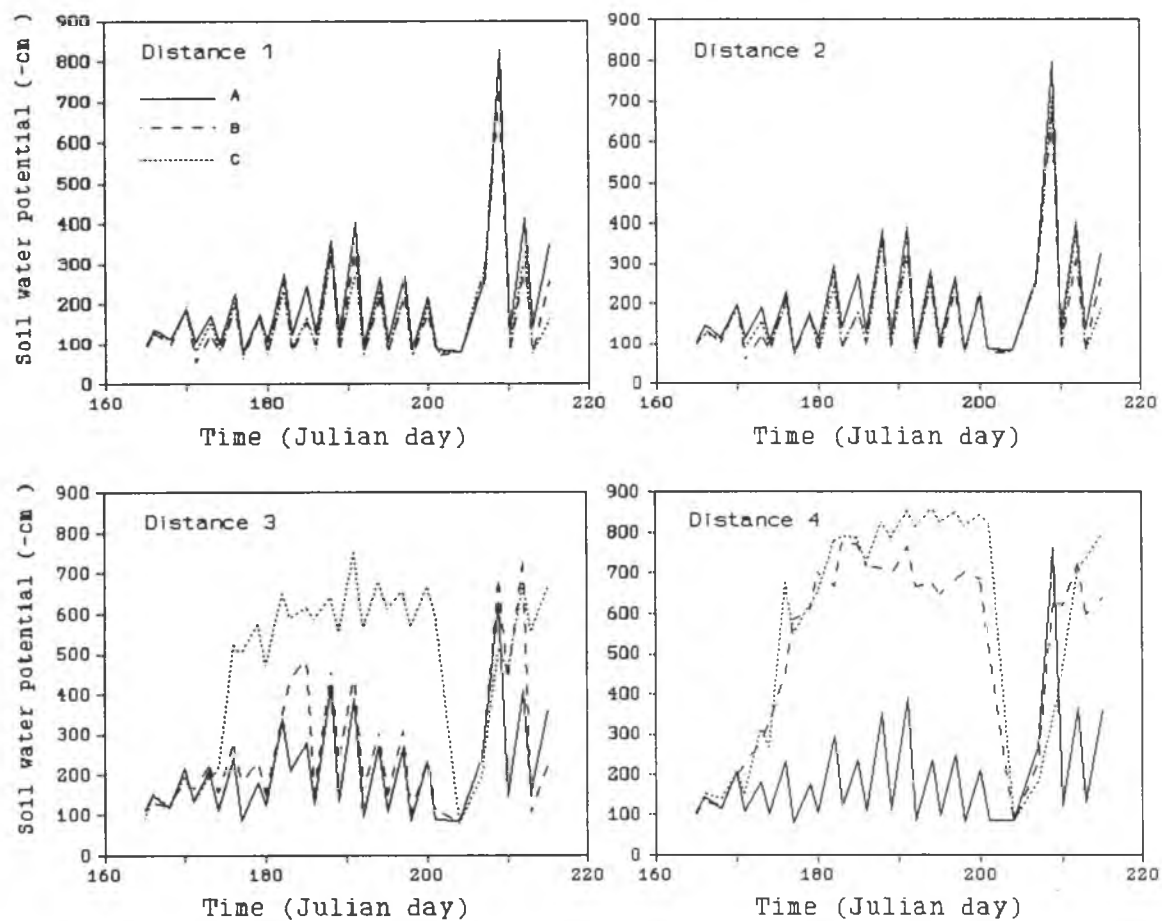


Figure 4 Variation in soil water potential versus time at 15 cm depth and different distances from line sources of treatments A, B and C (Refer to table 1 for actual distances).

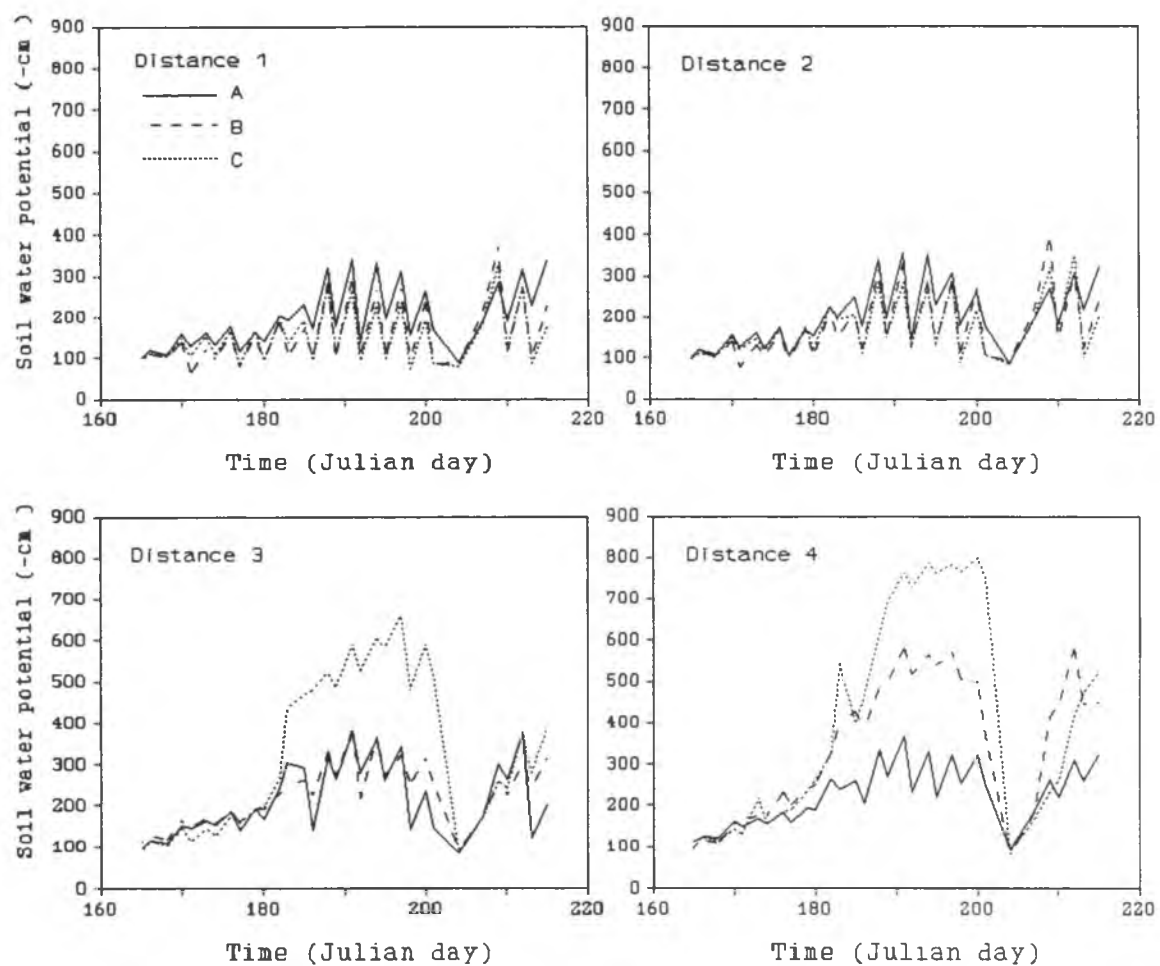


Figure 5 Variation in soil water potential versus time at 30 cm depth and different distances from line sources of treatments A, B and C (Refer to table 1 for actual distances).

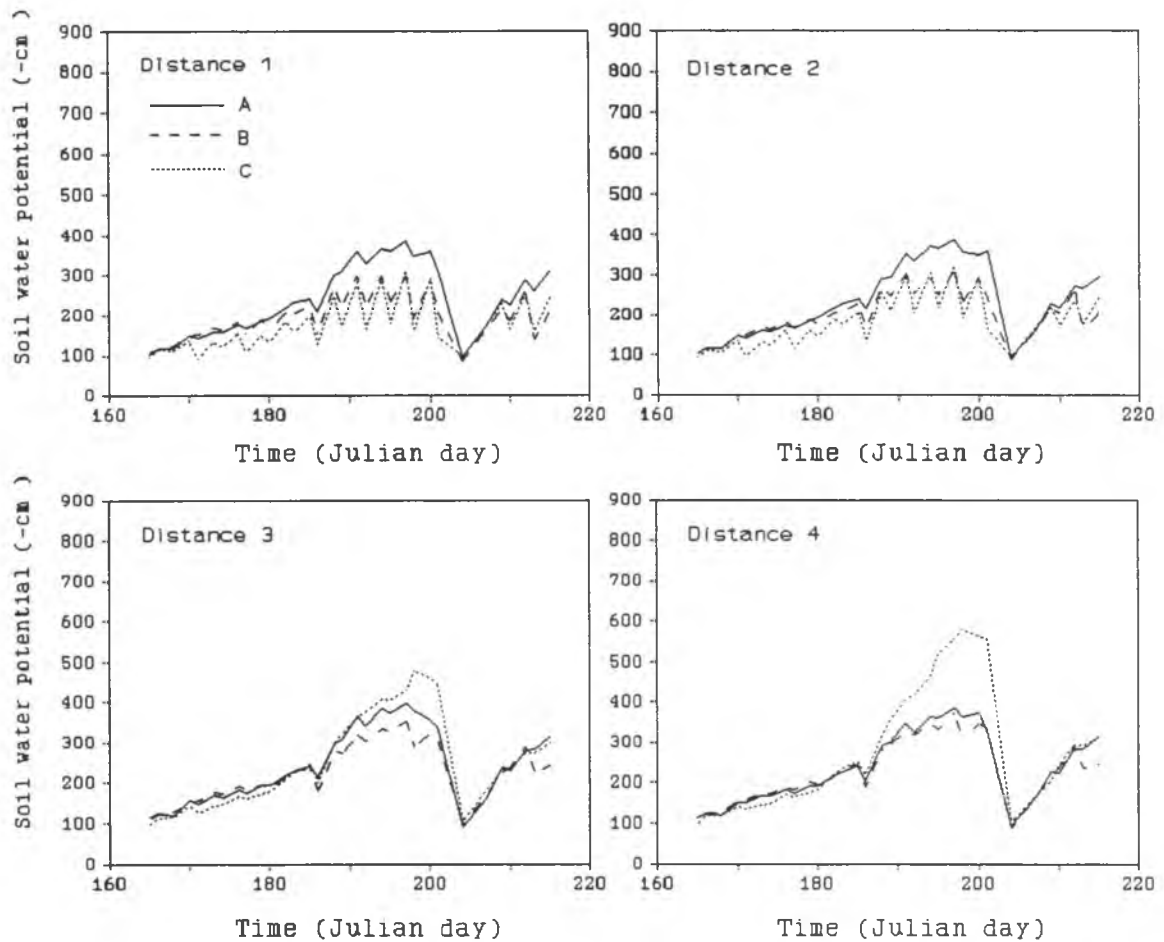


Figure 6 Variation in soil water potential versus time at 45 cm depth and different distances from line sources of treatments A, B and C (Refer to table 1 for actual distances).

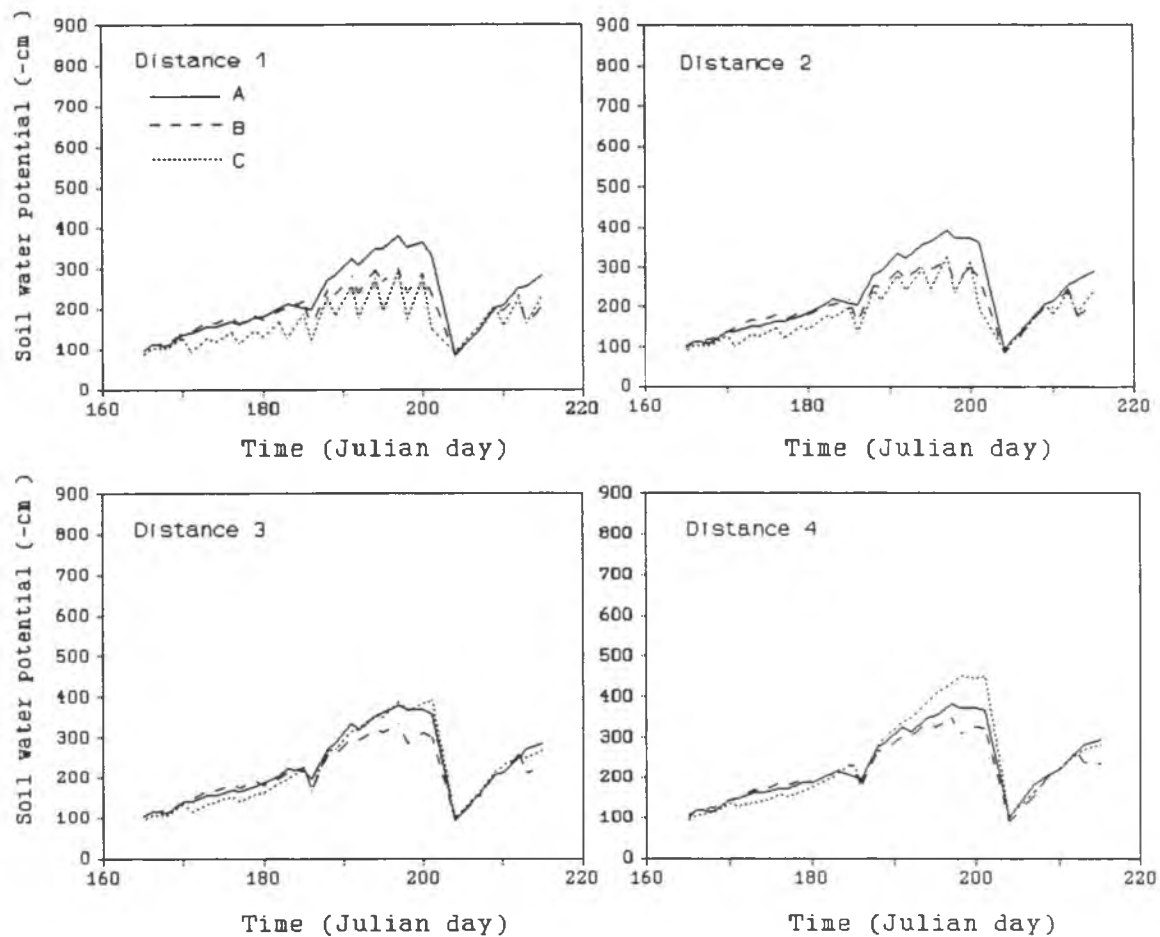


Figure 7 Variation in soil water potential versus time at 60 cm depth and different distances from line sources of treatments A, B and C (Refer to Table 1 for actual distances).

The SWP values of the three treatments were also plotted against time for four depths at four distances from line sources as shown in Figures 4 to 7. These figures show changes in SWP at different depths with respect to distances. The diagrammatic presentation of tensiometer arrays in Figure 2 of the Methods may help the reader interpret the SWP plots. There were no appreciable differences of the SWP located at and near the lines sources, i.e. those of first and second distances. The differences became greater at distances farther away from the line sources. The greatest variation in SWP was observed at midpoint between the line sources, i.e. the third distance of treatment A (the midway distance is 25 cm) and the fourth distances of treatments B and C (the midway distances are 50 and 75 cm). A more detailed discussion of SWP at midpoint between line sources is presented in the next section.

4.1.2 Soil Water Potential Midway between Line Sources

As mentioned earlier, one of the problems in drip irrigation system design is the selection of the proper combination of emitter spacing and discharge rate, either of a point source, or line source in order to provide the optimal wetted zones for a given combination of soil and crop. For a line source, approximate two-dimensional flow occurs and a wet region develops near the source. This was also observed in the field with zones of high SWP developing near line sources, and zones of low SWP (dry soil) appearing between the line sources. At the cessation of infiltration, movement of water through the soil profile continued and the near surface regions started to become depleted of water as plant water uptake, drainage and evaporation occurred. As pointed out, the driest point in the profile is normally at the soil surface, midway between the sources (Warrick et.al,1979). Such a value has been used as a reference point or as one of the parameters defined in soil water models, thus contributing toward the quantification of design and operation of drip irrigation. Bresler (1978) suggests a procedure to estimate the spacing between emitters as a function of discharge rate and soil water potential midway between emitters (h_c). This method can also be applied to the spacing of line sources. The midway soil water potential (h_c) must be determined before any emitter - discharge selection is made. The selection of h_c

is somewhat arbitrary, because of the uncertainty involved in the response of plants to partially wetted soil (Bresler, 1978). Thus, the adequacy of this value to represent the integrated water potential in the root zone is unknown. The midway between line sources is a point where the overlapping of wetted zones could be observed. Also, the h_c and size of the wetted zone are dependent on both soil (in terms of K_s and α) and irrigation system (in terms of spacing and discharge). It seems that the h_c can be used as a soil water variable as required by the crop for the drip irrigation design problem. The question arises about the depth of h_c if a single value is to be used quantitatively.

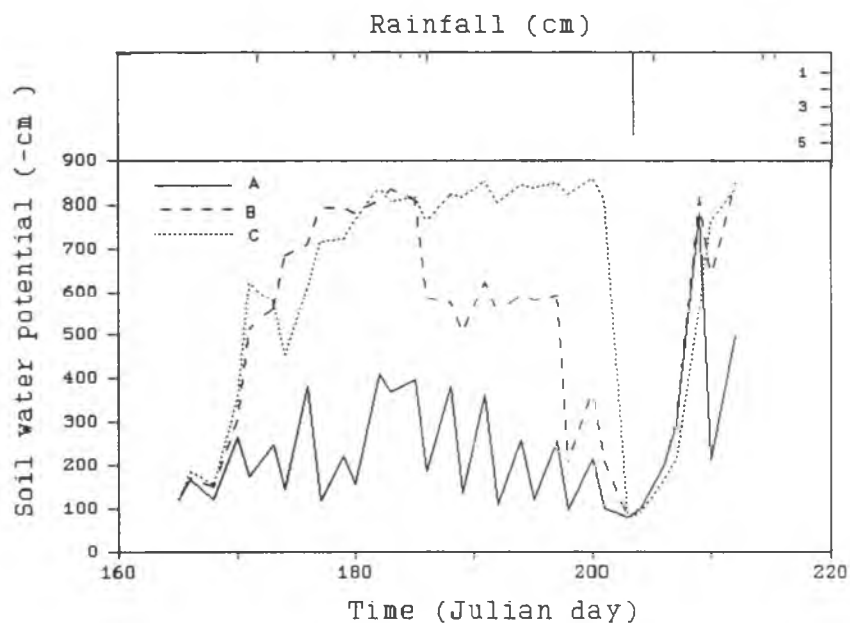


Figure 8 Soil water potential at the surface midway between line sources versus time for different spacings 50, 100 and 150 cm. (Treatments A, B and C respectively).

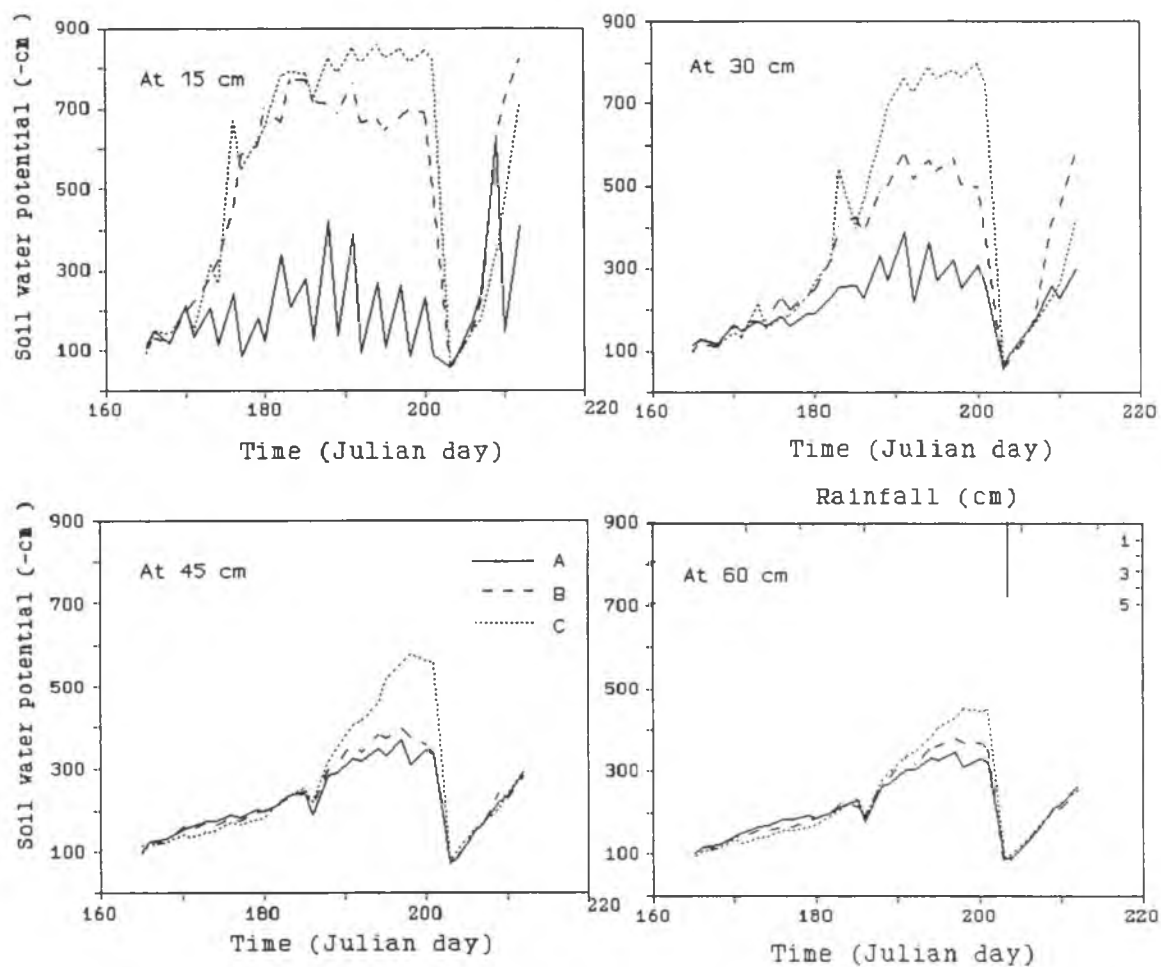


Figure 9 Soil water potential midway between line source for 15, 30, 45 and 60 cm depths and different spacings of line sources 50, 100 and 150 cm.

Midway SWP between line sources obtained from the field experiment are presented in the Figures 8 and 9. These figures show the effect of spacing of line sources on midway SWP values from the soil surface to 60 cm depth of the root zone. The SWP values become lower (more negative) as spacings become wider. The differences in SWP at the midway

of treatments B and C from treatment A are obvious (Figures 8 and 9) at the surface, 15 and 30 cm depths, but there was little difference at 60 depth. This implies that the water moves from the line sources vertically as well as horizontally and begins to overlap at lower depths while the surface remains quite dry, particularly at the midpoint between the lines sources. Evaporation has little effect at deeper depths as compared to the surface, although it may cause upward flow of water after a certain period of irrigation time. The field data indicated that the h_c value at the surface may result in over-estimation, on the other hand, the value at depths below 45 cm may give an underestimated value. Therefore, a h_c value between the depths of 15 to 30 cm seems most appropriate. However, the direct physical significance in relation to crop response is questionable (Russo, 1984). How the corn crop in this study responded to soil water potential as represented by h_c is presented in section 4.2.4.

4.1.3 Soil Water Potential Distribution Patterns

The water movement from an isolated emitter (a point source) is three dimensional; when the emitters are close together in a line (a line source) the flow may be approximated as two dimensional (Schwartzman and Zur, 1987; Warrick and Lomen, 1983). Soil water distribution in the profile is determined by soil properties, the method of application and the amount of water applied and withdrawn from the profile. In the case of a line source, the wetted soil volume is generally assumed to depend on hydraulic properties of the soil (K_s and α), on source discharge per unit length, and total amount of water per unit length. It is noted that during the field experiment, irrigation time was varied in order to deliver the same amount of water per unit area per treatment using the same discharge rate for all treatments. This results in differences in total amount of water per unit length, not per unit area.

Two dimensional distributions of SWP in the root zone of sweet corn before and after irrigation are given in Figures 10 to 12. The figures for the first growth period (a period before the treatments started) are not presented because the soil was uniformly wet for all treatments. The seasonal averaged SWP was also plotted to give general picture of the SWP distributions resulting from different spacings of line sources (Figure 13).

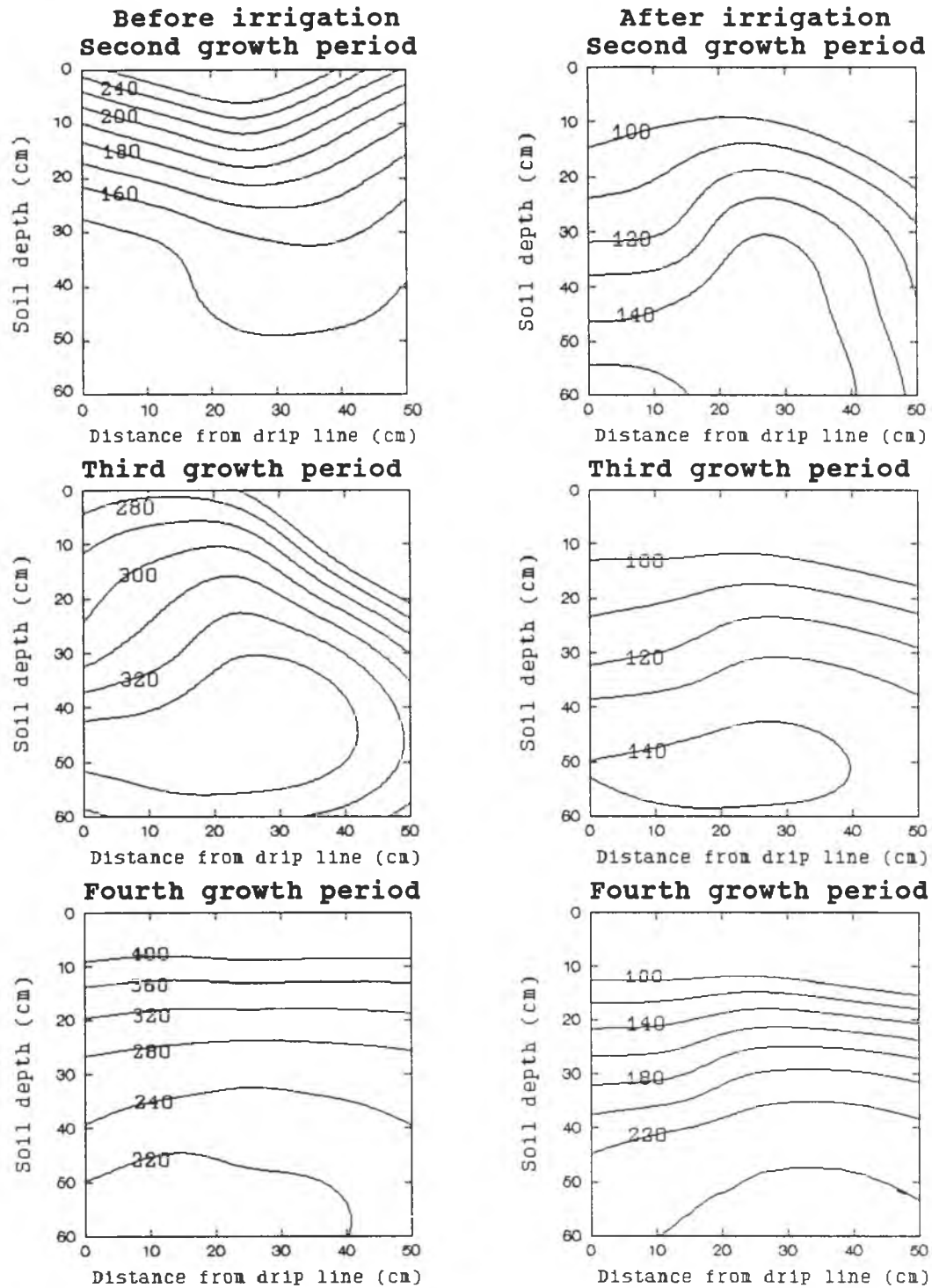
Treatment A:

Figure 10 Soil water potential distributions in the root zone for 50 cm spacing of line sources (Treatment A) before and after irrigation during the second, third and fourth growing periods of sweet corn crop.

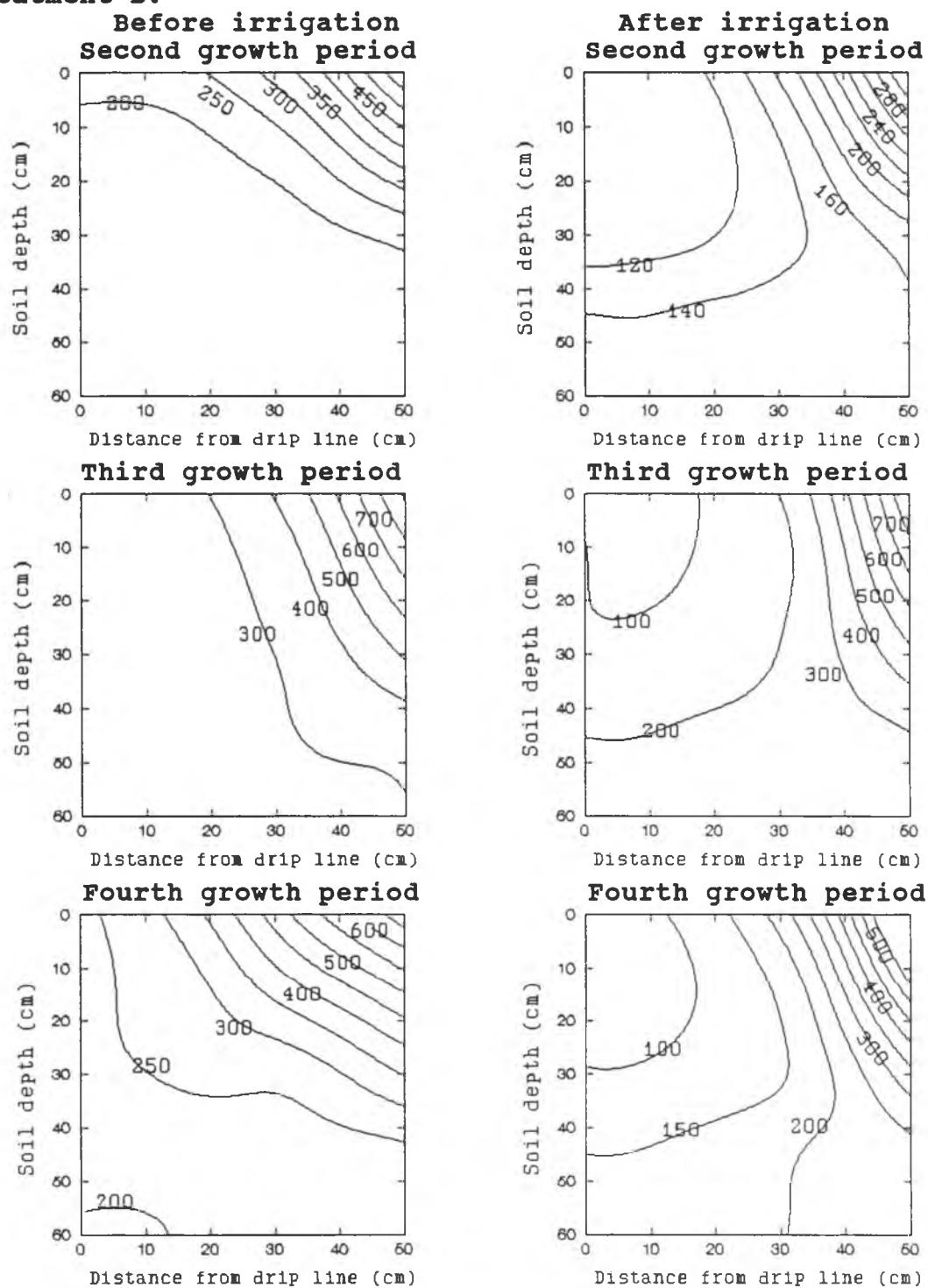
Treatment B:

Figure 11 Soil water potential distributions in the root zone for 100 cm spacing of line sources (Treatment B) before and after irrigation during the second, third and fourth growing periods of sweet corn crop.

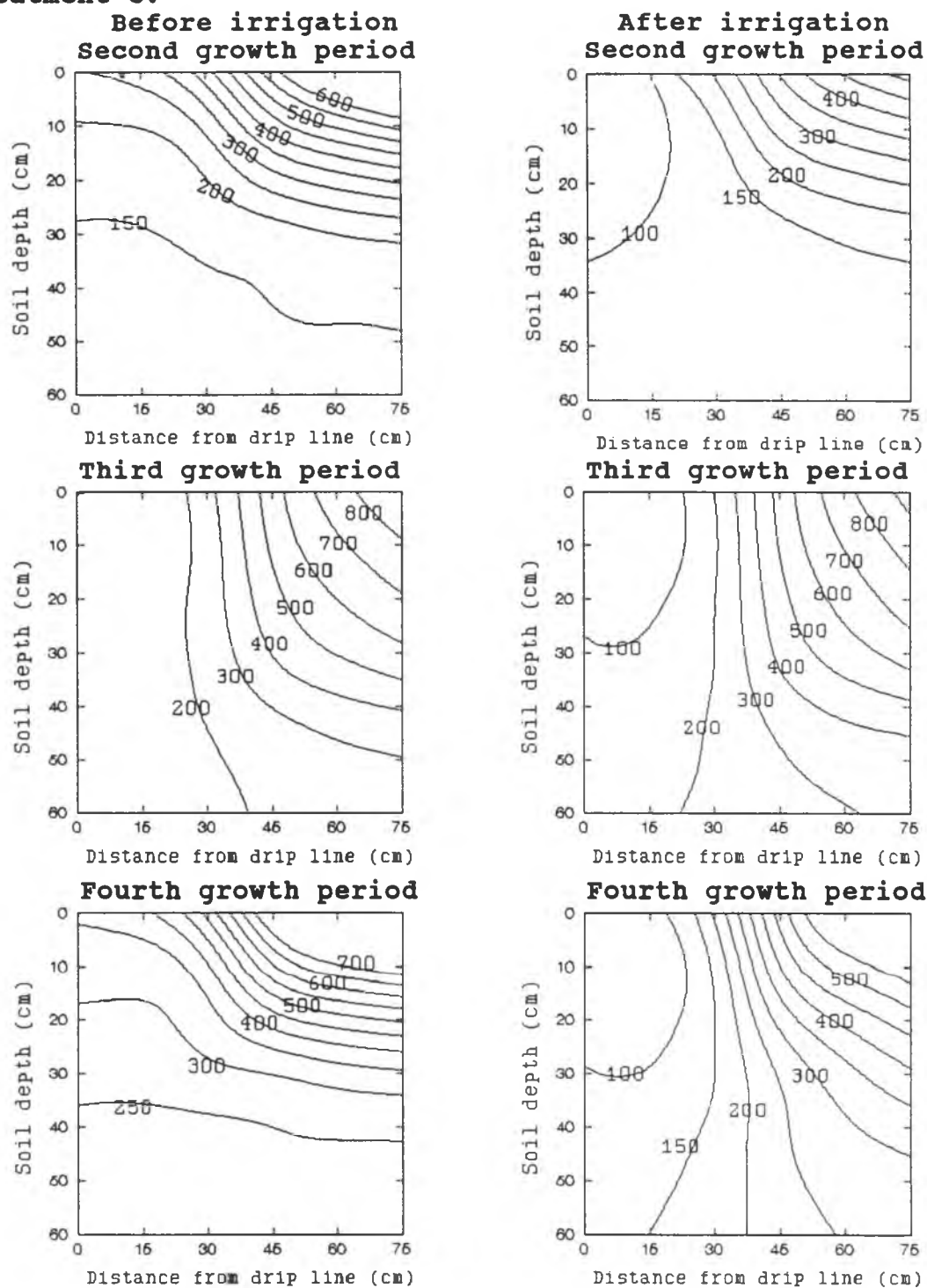
Treatment C:

Figure 12 Soil water potential distributions in the root zone for 150 cm spacing of line sources (Treatment C) before and after irrigation during the second, third and fourth growing periods of sweet corn crop.

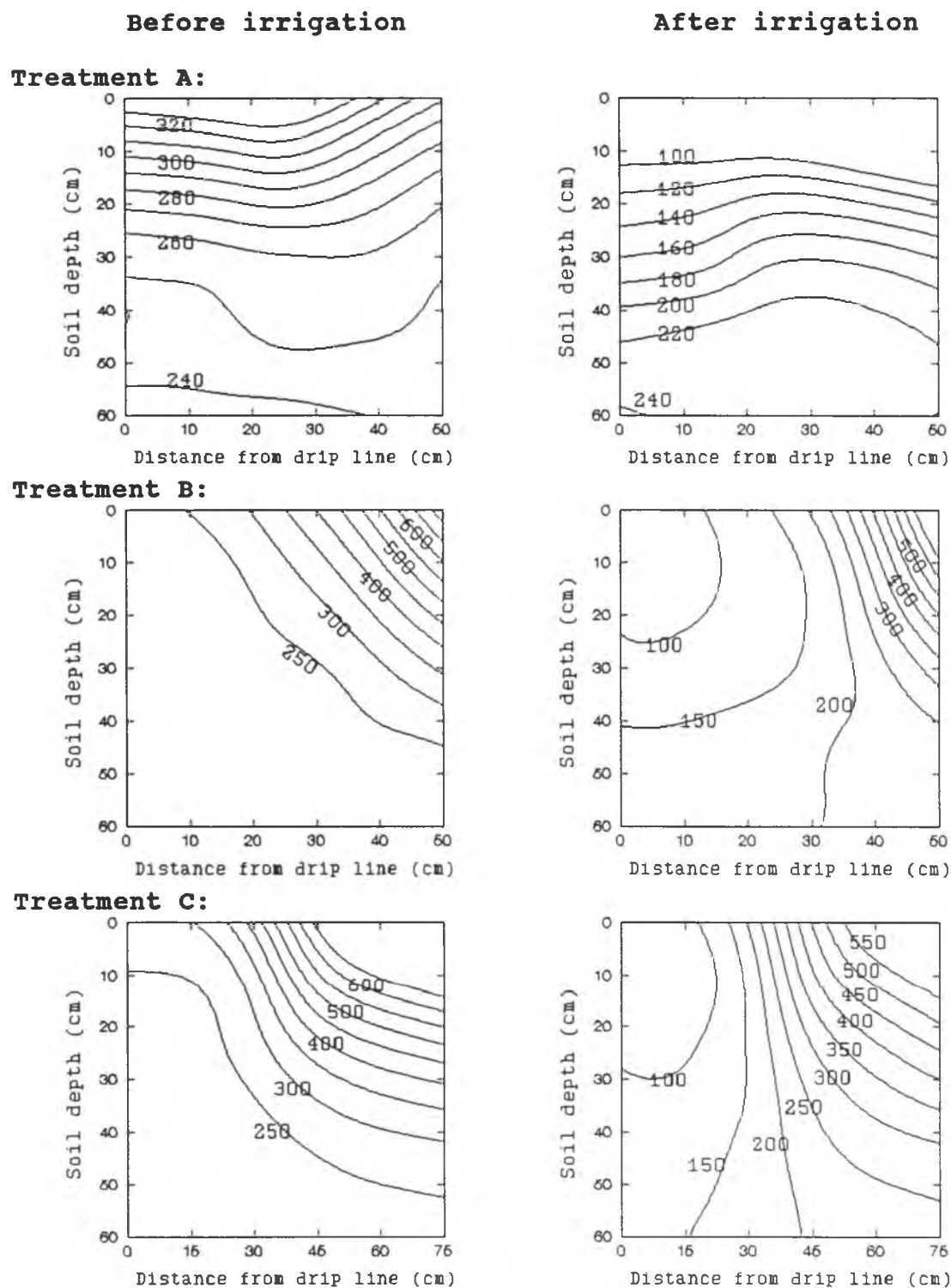


Figure 13 The seasonal averaged soil water potential distributions in the root zone of sweet corn crop under different spacings of line sources (50, 100 and 150 cm for Treatments A, B and C respectively).

Figure 10 shows that SWP distributions during the growing season for treatment A was fairly uniform for each depth interval, especially below 15 cm depth, as indicated by contours of equal SWP, because the 50 cm spacing of line sources was close enough to allow lateral flow from each line to partially overlap and form connecting contour lines between sources. The field data indicated that after a few days of irrigation the soil water profile depleted due to evaporation and continued water uptake by plants. Rice (1975) found that water patterns rapidly changed near the surface during the first few days after irrigation. The range of SWP between the surface and 60 cm depth of the root zone was not markedly different for treatment A. It is believed that such a range of SWP provides a suitable moisture environment for sweet corn, as indicated by relatively uniform growth and reasonably good yield (section 4.2.1).

The patterns of SWP distributions change as the spacings between line sources become wider (treatments B and C). The two dimensional distributions of SWP up to the midway between the line sources under treatment B (100 cm spacing) are shown in Figure 11.

Zones of high (less negative) SWP appeared near the line sources and zones of dry soil were developing between the line sources. The driest point was normally found at the surface midpoint between the lines, especially before

irrigation. The soil at this area remained dry most of growing season and reached a minimum (driest) during the third growth period. This may be due to the fact that for a given amount of water applied at given discharge rate, the water moved more in a vertical direction rather than in a horizontal direction, so that overlapping zones did not develop, especially at shallow depth. In addition to surface evaporation, continued water extraction by plants located between the line sources caused the decreasing of SWP and eventually its distribution in the soil profile.

The SWP distribution patterns under treatment C (150 cm spacing) differed from those of treatments A and B. Figure 12 suggests that after one day of irrigation, the increase of horizontal flow from the line source was less effective as compared to the increase in vertical flow. As a result, the somewhat oval shaped wetting patterns developed below the line sources. After two or three days of irrigation the SWP progressively decreased (more negative) with distance from the line sources, particularly at the surface to about 30 cm depth. The driest point of soil profile for treatment C was observed at the surface midpoint between the line sources, even more so as compared with those of treatments A and B.

A study by Santo (1975) on the Molokai soil (not far from this study site) concluded that for this soil, deep percolation was minimal due to the plow pan, although

gravitational effects could result in deep vertical percolation with a long irrigation time. His results are in agreement with results obtained from this study, since the irrigation time for treatment C required the longest period in order to apply the same amount of water as given for treatments A and B. Moreover, Schwartzman and Zur (1987) concluded that an increase in the amount of water in the soil (per unit line length) tends to increase the wetted soil depth considerably more than the wetted soil width.

Figure 13 is presented to give an overview of the effect of spacings of line sources on SWP distribution patterns. Two sets of SWP data, before and after irrigation, were simply averaged throughout the growing season of the sweet corn crop. Figure 13 clearly shows differences in patterns of SWP distributions among the three treatments before and after irrigation. The wetted patterns before irrigation may be affected by upward flow of water, because evaporation and absorption by plants decreased the water of the surface soil, thereby decreasing its water potential and causing upward movement against gravity as indicated by before-irrigation data. The results suggest that a relatively uniform soil water profile can be obtained by adjusting spacing of line sources for any given discharge rate and soil so that overlapping of wetted zones can be developed as demonstrated by treatment A.

4.2 Field Experiment: Relationships between Soil Water Potential and Crop Growth and Yield

4.2.1 Soil Water Potential Distribution versus Crop Yield

Sweet corn was planted on May 22, 1989. Irrigation water was applied daily following planting to facilitate germination. Emergence was fast and a good stand was obtained. Plants were thinned to the same population for each treatment (90,000 plants per hectare) with one stalk per plant. All treatments were subjected to different soil water potential distributions due to differences in spacings of line sources, i.e. 50, 100 and 150 cm spacings.

It is noted that drip lines or line sources were installed for every plant row of treatment A (50 cm line spacing) whereas treatments B (100 cm line spacing) and C (150 cm line spacing) consisted of one and two plant rows without drip lines, respectively. Plant rows with drip lines are referred to as wet rows and the plant rows without drip lines as dry rows (Figures 1 and 2). Thus, treatments B and C could be split into two groups, i.e. B-wet and B-dry for treatment B, and C-wet and C-dry for treatment C. This field experiment was analyzed as a split plot design, the main-plots corresponding to line spacings and the sub-plots corresponding to the wet and dry portions of main-plots.

The crop response to soil water potential distribution was based on marketable ear yield, mean ear diameter and length, total fresh weight and total dry matter production, plant height and leaf area index (LAI). Growth and

development of the crop were analyzed by measuring plant height weekly, and leaf area index and rooting depths on a regular schedule according to stages of growth. Corn was harvested on August 5, 1989, and data were collected on total number and weight of marketable ears. Ten randomly selected marketable ears were husked, and weights, average lengths and diameters were recorded. Whole plant samples were also taken for analysis of fresh and dry matter production.

The average heights of sweet corn plants were fairly uniform in all plots before the irrigation treatments started. Visual observation suggested that plants in rows with drip lines (wet rows) were taller than plants in rows without drip lines (dry rows). The plant heights of treatment A (50 cm spacing) were relatively uniform, because all plant rows within the experimental plot were uniformly wetted by drip lines. Although there were differences in heights between plants on wet and dry rows, the average heights were not different among the three treatments until about 40 days after planting. The significant differences in average plant heights were noticeable about 50 days after planting, and especially so at maturity stage (Figure 14). Mean plant height of treatment A was significantly different from those of treatment B and C but there were no significant differences between treatments B and C.

Plant heights for the last measurement were slightly decreased with maturity.

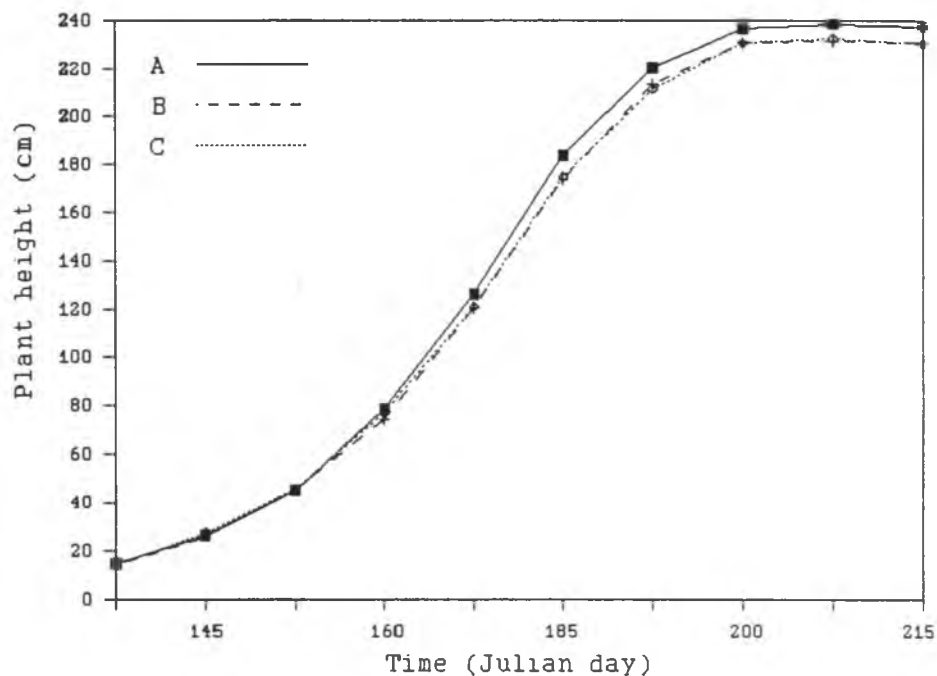


Figure 14 Average heights of sweet corn plants under different spacings of line sources (50, 100 and 150 cm) for treatments A, B, and C, respectively.

The analysis of variance indicated that spacings of line sources (for which different patterns of soil water potential developed) had a significant effect on plant heights. Plants on wet rows were taller than plants on dry rows, because the plants on the dry rows received less water than those of the wet rows, as zones of dry soil were observed between line sources.

The rooting depths were measured at different growth periods by an excavation method. Root distributions were also observed. The rooting depths varied with time during the growing season from 25-30 cm at the start of the treatments to 65-70 cm at the end of the experiment. Roots of plants without drip lines (dry rows) were less developed than those of plant rows with drip lines (wet rows). Thus the root distributions of plants on wet rows were more dense and had better uniformity than those of plants on dry rows of treatment B and C. At maturity, high root density appeared at depths 5-30 cm and less density at lower depths because of a plow pan layer which was evident at depths of approximately 35 to 40 cm. The effect of the root system on soil water potential distribution probably increased with crop growth stages until maturity. In addition, changes in water uptake with depth and time are believed to be due to differences in root density, root activity and changes in hydraulic characteristics over space and time (Van Bavel, 1968). Arya (1975) concluded that changes in soil water potential patterns with crop growth reflect the changing distribution of roots in the soil profile. These changes should also affect relative water losses from the different soil layers. Generally, a good root distribution was obtained under treatment A, which provided a fairly uniform water application without developing serious dry zones as compared with treatments B and C.

Table 2 Yield and leaf area index of sweet corn (Super sweet #10A) as affected by different spacings of drip line sources.

Treatment	Spacing of line sources (cm)	Leaf area index	Marketable ear yield		Plant yield		Total yield	
			Fresh	Dry	Fresh	Dry	Fresh	Dry
A	50	a 4.22	a 2872	a 618	a 4319	a 824	ab 7191	a 1442
B (wet)	100	a 4.13	a 2791	a 602	a 3910	a 758	b 6701	a 1359
B (dry)	100	b 3.44	b 2174	b 471	bc 3141	b 590	c 5315	b 1061
C (wet)	150	a 4.20	a 3056	a 652	a 4523	a 837	a 7579	a 1489
C (dry)	150	b 3.58	b 2100	b 419	b 3294	b 605	c 5394	b 1024

Leaf area index (LAI) of sweet corn plants on wet rows and dry rows was significantly different among treatments (Table 2). Table 2 also shows marketable ear yield, plant yield (stover) and total yield (ears plus stovers). Yields of sweet corn did not differ among the wet rows of all treatments, but they were significantly different between yields obtained from wet rows and dry rows (Appendix B). In considering yield from entire harvest areas of all line spacing treatments, the marketable ear fresh weight, plant fresh weight and total fresh weight were not significantly different between treatments A and B, and between treatments B and C, but there was a significant difference between treatment A from treatment C.

Table 3 Overall means for selected sweet corn parameters

Treatment	Spacing of line source (cm)	Marketable ear yield			
		weight 10 ears with husk	weight 10 ears without husk	length	diameter
		g/m ²		cm	
A	50	3034 ab	2077 ab	20.2 a	14.7 a
B (wet)	100	3062 ab	2128 a	20.2 a	14.8 a
B (dry)	100	2673 bc	1826 b	19.3 ab	13.8 b
C (wet)	150	3145 a	2167 a	20.3 a	14.8 a
C (dry)	150	2455 c	1676 bc	18.7 b	13.6 b

Table 3 presents means for ten randomly selected marketable ears. Statistical significance at the 5% level for any treatment is separated by different letters following each value. The analyses of yield parameters indicated that marketable ear weight, plant fresh weight and dry weight, total fresh weight and dry weight, selected ear weight (with and without husks), ear length and ear diameter were decreased as distance between a plant row and a drip line increased, as demonstrated by plant rows without drip lines (dry rows) under treatment B and C. Note that treatment A was not split into wet and dry rows because a drip line was installed for each plant row. Tip fill of ears and blank kernels were also observed for selected marketable ears. Ears from wet rows of all treatments showed good tip fill with only a few blank kernels as compared with ears obtained from dry rows. This suggests that the tip fill increased in zones of higher water

availability, and number of blank kernels was increased with lower water availability at greater distances from drip lines where dry zones developed. However, the number of kernel rows was not significantly different among treatments.

The crop response data suggest that spacing between line sources affected soil water potential distribution, consequently affecting yields of sweet corn. Therefore, spacing of line sources and plant rows are important when designing drip irrigation for any particular crop. It seems to be ideal to place a drip line for each plant row, to ensure that each plant row receives enough water for good plant growth and yield. In some cases, one drip line may provide sufficient water for two crop rows. As demonstrated by Phene and Beale (1979), yields of sweet corn were not affected by twin-row bed spacing with one drip line placed between rows, in comparison with one drip line per crop row. However, this study indicated that treatments A and B (50 and 100 cm line spacings) with 50 cm spacing of plant rows provided reasonable yields of sweet corn because the dry zones of soil that developed between line sources of treatments A and B, compared to treatment C, were not so critical as to cause markedly reduced yields.

4.2.2 Soil Water Potential at Different Depths and Distances versus Crop Growth and Yield

Soil water potentials were measured using tensiometers before and after irrigation at four depths and four distances from a drip line (line source) of each treatment (Figure 2). These data were then correlated with crop growth and yield based on marketable ear yield, mean ear length and diameter, total fresh weight, total dry matter production, leaf area index (LAI) and plant height. The purpose was to determine reasonable relationships between soil water potential distribution and crop growth and yield under drip irrigated sweet corn.

Tensiometers have previously been used to control irrigation, to determine the optimum soil water potential at which to irrigate crops, to evaluate yield response to soil water conditions, to evaluate crop irrigation model predictions of soil water balance, and to examine the water extraction patterns of various crops (Gardner, 1964; Phene and Beale, 1976; Cary and Fisher, 1983; Hook et al., 1983; Oron, 1984; Fyen et al., 1985; Pouge and Pouly, 1985). However, a serious difficulty encountered in attempting to relate soil water to crop response is the fact that the water content in the root zone varies in both time and space (Gardner, 1964). Morgan et al. (1980) suggest that dynamic response relationships are needed because with irrigation scheduling the decision of when to irrigate depends upon the crops response to water. Generally, it is important to

maintain the soil water potential within a given range for optimal crop production (Kramer, 1983). In irrigation technology, more knowledge about the relationship between soil water potential and crop yield is still needed, particularly for a crop under drip irrigation. The success of a drip system depends upon identifying the optimal soil water potential and distance and depth of tensiometer or sensor relative to the water outlet (Levin et al., 1985).

Table 4 Soil water potential at different depths (in the plant row) throughout the growing season of sweet corn.

Treatment	Replication	Soil Water Potential (-cm of water)				
		15 cm depth	30 cm depth	45 cm depth	60 cm depth	means (all depths)
A	1	217	223	219	218	219
	2	213	188	247	237	221
	3	188	186	223	216	203
B-Wet	1	160	146	182	195	171
	2	184	155	217	212	192
	3	170	155	183	191	175
B-Dry	1	499	331	228	220	295
	2	495	329	224	223	318
	3	503	401	247	234	346
C-Wet	1	185	165	170	169	172
	2	145	141	175	165	157
	3	185	171	177	166	175
C-Dry	1	587	398	254	233	365
	2	499	321	235	206	315
	3	554	367	249	225	349

To evaluate the relationship of soil water potential and crop yield, the soil water potential values located at particular crop rows where yield parameters were obtained, were averaged throughout the growing season for four different depths as shown in table 4.

Table 5 Yield parameters of sweet corn (Super sweet #10A) as affected by different spacings of line sources.

Treatments	Replication	Fresh Weight			Dry Matter Production			Leaf Area Index	Plant Height
		plant	Ear	Total	plant	Ear	Total		
		g/m ²			g/m ²			cm	
A	1	4598	2640	7238	858	580	1438	4.26	238
	2	4412	3193	7605	844	696	1541	4.16	237
	3	3947	2782	6730	770	577	1347	4.25	237
B-Wet	1	3925	2594	6519	733	579	1312	4.06	233
	2	4314	3142	7457	830	655	1486	4.12	238
	3	3491	2635	6126	709	569	1279	4.22	237
B-Dry	1	3292	2255	5547	607	479	1087	3.52	231
	2	3202	2370	5572	598	527	1126	3.44	224
	3	2928	1896	4824	564	406	970	3.35	222
C-Wet	1	4587	3129	7716	865	687	1552	4.20	236
	2	4166	3018	7184	749	601	1350	4.12	237
	3	4816	3021	7837	895	668	1564	4.27	239
C-Dry	1	3117	1906	5023	569	377	947	3.56	233
	2	3750	2397	6148	689	492	1182	3.65	223
	3	3014	1997	5011	556	386	942	3.52	222

Data in table 5 show crop variables, including yields, leaf area index (LAI), and plant height of sweet corn. Treatments B and C were split into wet rows (crop rows with drip lines) and dry rows (crop rows without drip lines). The yields of sweet corn were significantly affected by spacings of line sources. There were highly significant differences in yields, LAI and plant height between wet rows and dry rows, indicating the reduction in yields due to distance from a line source. The soil water potential values were also significantly different between wet rows and dry rows but they were not significantly different among rows with drip lines. Data presented in table 4 and 5 were then correlated (Table 6).

Table 6 Correlations of sweet corn yield parameters and soil water potential at different depths.

Yield Parameters	Soil Water Potential (-cm)				Average
	15 cm	30 cm	45 cm	60 cm	
	r values				
Plant fresh weight	0.81	0.71	0.48	0.41	0.78
Ear fresh weight	0.87	0.78	0.48	0.37	0.84
Total fresh weight	0.87	0.76	0.49	0.41	0.83
Plant dry weight	0.86	0.75	0.49	0.39	0.82
Ear dry weight	0.88	0.76	0.50	0.36	0.84
Total dry weight	0.87	0.77	0.51	0.38	0.85
Leaf area index	0.95	0.84	0.56	0.41	0.91
Plant height	0.93	0.89	0.55	0.36	0.92
* Ear length	0.80	0.79	0.58	0.38	0.80
* Ear diameter	0.93	0.87	0.61	0.41	0.92
* No. of kernel rows	0.55	0.45	0.48	0.36	0.54

* These parameters are based on 10 representative ears without husk

These data indicate that soil water potential at the 15-cm depth located within a crop row was highly related to yield parameters as compared with the soil water potential at greater depths. The soil water potential values at the 60-cm depth show the least correlation to crop yield because only a small variation in soil water potential occurred at greater depths, as shown previously in section 4.1.1. To maintain the optimum levels of soil water in irrigated fields, one common criteria for 'need to irrigate' is the soil water content or the soil water potential at a specific depth. Based on the data obtained in this study, the soil water potential value at 15-cm depth is recommended for such purposes. It has been shown in field trials that

measurement of soil water potential at the 15-cm depth works well from a practical standpoint (Cary, 1981; Cary and Fisher, 1983). Optimal ear yield of sweet corn was produced with drip irrigation when the soil water potential at 15-cm soil depth was controlled at about -200 cm (Phene and Beale, 1976). According to Phene and Beale (1976), irrigation should be started before the soil water potential at 15-cm depth decreases below -400 cm (the water source strength-limiting soil water potential, and causes plant water stress). These authors believed that water content above 15 cm may be strongly affected by evaporation as compared to transpiration, while changes in soil water potential at lower depths, i.e 30-40 cm, are much less responsive to evapotranspiration than those at 15 cm. Therefore, the soil water potential at the 15-cm depth is the simplest fundamental criteria available for determining the imminent need for irrigation as related to crop response. The lower (more negative) values of soil water potential were usually known at the start of each irrigation or before irrigation. Also the installation depth and critical value of the soil water potential are limited and determined by the soil hydraulic properties, the water extraction patterns of roots, the evapotranspiration rate, the bottom boundary condition of the soil profile and crop response to water stress (Fyen et al., 1985). Pouge and Pooley (1985) suggest locating tensiometers 30-40 cm from the emitter at 30 cm and

60 cm, with an added 90 cm depth on the deeper root crops. The studies on vegetable crops by Goyal and Rivera (1985) were successful with water application rates based upon readings of tensiometers installed at 15, 30, and 45 cm below the soil surface. The irrigation was initiated when the soil water potential, as indicated by the tensiometers, was -450 cm and was terminated at -150 cm. The soil water potential of -200 cm or about -0.2 bar (20 KPa) was often set as a threshold for automatically opening and closing the water supply.

Data from a supplementary experiment conducted along with the main experiment (Figure 1b) demonstrated the relationships between distances from a drip line and soil water potential and crop yields. Figure 15 shows soil water potential values at different depths and Figure 16 shows averaged values over all depths as affected by distance from a drip line. There was little variation in soil water potential at all depths near the drip line. The soil water potential values generally decreased (more negative) as distance increased. The greatest variation was observed at 15 and 30 cm depths. Yield of sweet corn expressed as total dry matter production (g/plant) was affected by distance from the drip line as shown in Figure 17. Similarly to soil water potential, when distance from a drip line increased, the yield generally decreased. Figure 18 indicates that yield diminished with decreasing soil water potential.

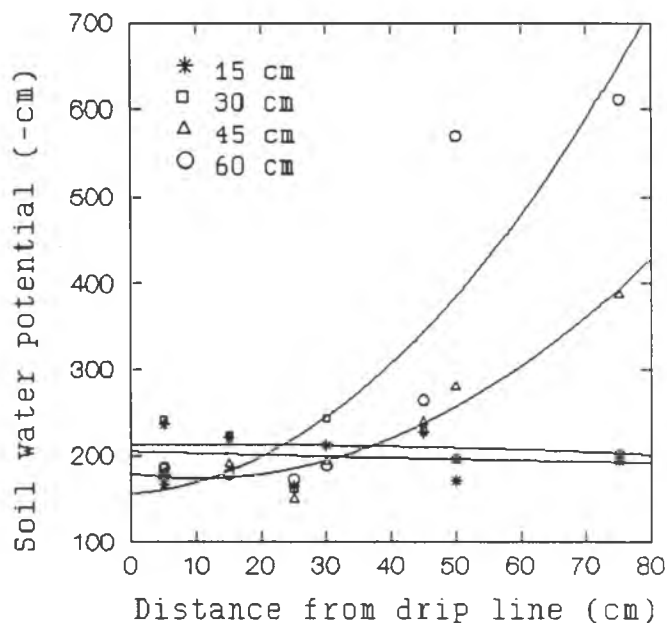


Figure 15 Soil water potential throughout the growing season of sweet corn versus distances from a drip line at different soil depths (Supplementary experiment).

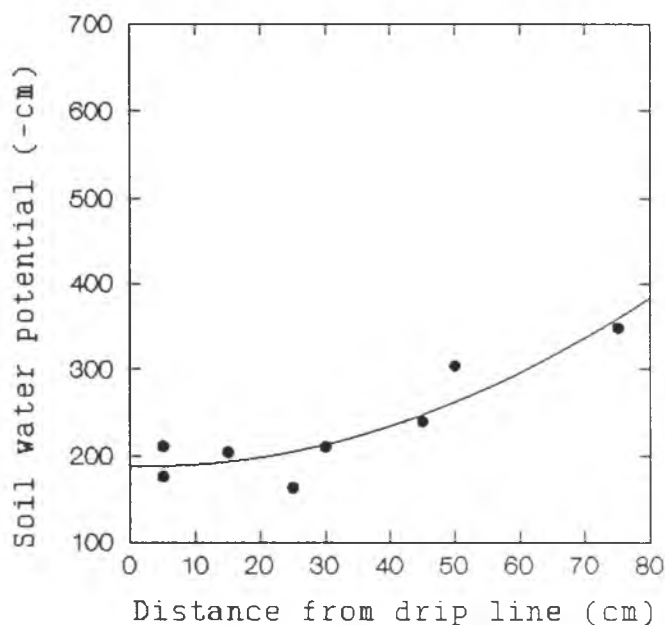


Figure 16 Average soil water potential over depths throughout the growing season of sweet corn versus distances from a drip line (Supplementary experiment).

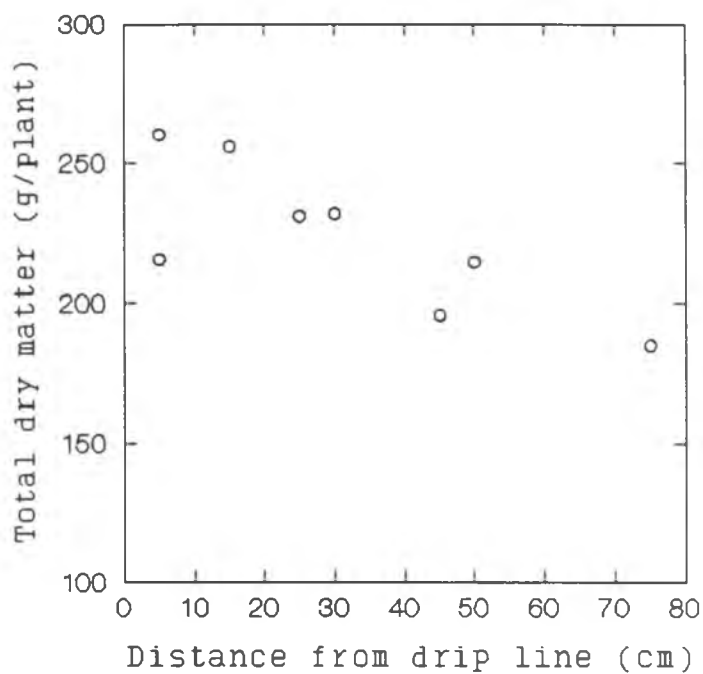


Figure 17 Total dry matter production of sweet corn as affected by distances from a drip line (Supplementary experiment).

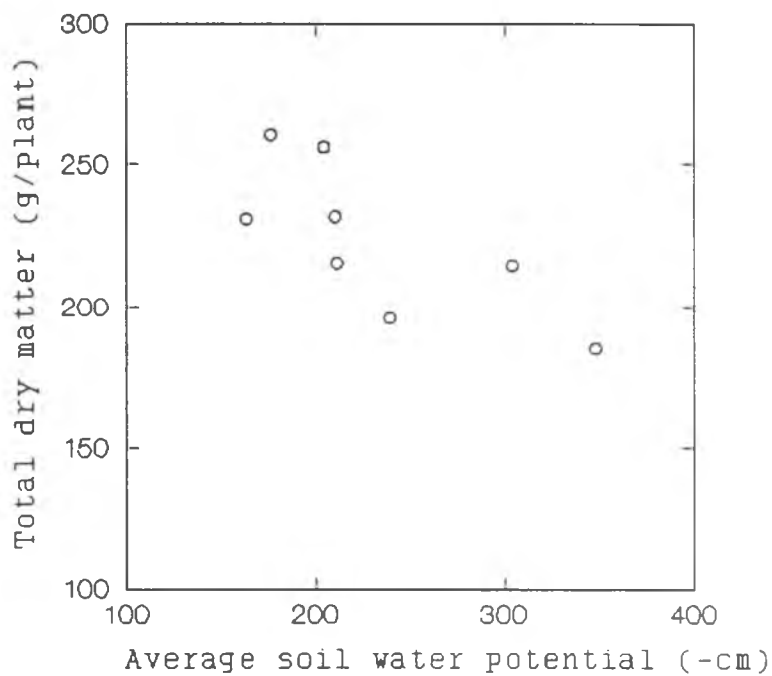


Figure 18 Relationship between yield of sweet corn as total dry matter production and average soil water potential throughout growing season (Supplementary experiment).

4.2.3 Representative Values of Soil Water Potential versus Crop Growth and yield

Soil water potential at a given depth in the root zone may correlate well with crop response and provide a useful basis for irrigation. Even so, a representative value of soil water potential over the entire root zone may still be needed in order to have a clearer understanding of how a crop responds to water conditions in the root zone. Good correlations have been reported between integrated values and crop yield (Taylor, 1952; Denmead and Shaw, 1962; Karamanos, 1980; Wierenga and Saddig, 1985). The difficulties in calculating such representative soil water potential values may be due to the fact that soil water content and potential vary in both space and time. In addition, the problems in calculating such values arise mainly from non-uniformity of root density within the soil profile affecting water distribution, as well as from the variation in root resistance to water flow from different layers of the root system (Taylor and Klepper, 1975).

To obtain a representative value for soil water potential within the root zone in this study, three methods were considered and evaluated: i) A simple averaging of soil water potential over depths and throughout the growing season; ii) the method developed by Taylor (1952), involving fitting polynomial regression equations to values of soil water potential from field data over both depth and time, then combining the two regressions equations and using a

double integral to give a representative (integrated) soil water potential for the root zone over a specified time interval. Taylor claimed that this approximation is adequate for many applications; iii) the method developed by Karamanos (1980), by which soil water potential values from individual soil layers were weighted according to the rate of soil water depletion in a soil layer at the time of measurement. This was assumed to approximate the rate of water absorption by roots. Soil water depletion was determined for periods between two samplings and the rate of depletion at a particular sampling was taken as the average depletion for two successive time intervals. According to Karamanos, this method is useful for field conditions since it reduces to a great extent the labor and ambiguity involved in sampling for root density at different depths.

The main purpose of integrating or averaging soil water potential was to condense and represent spatially and temporally varying soil water potential values by a single value for a given soil-crop combination in any season. To evaluate the methods of calculating representative values of soil water potential, results obtained from different methods were related to crop yield. Examples of calculating such values by the three methods are given in Appendix C.

By integrating the water distribution with depth and time, one can obtain a rough estimate of soil-water energy status in the root zone during the time interval considered.

In method I, soil water potential values were simply averaged over all depths throughout the growing season for all plots within a given treatment. It should be emphasized that only soil water values measured within particular crop rows were considered in order to correlate integrated values of soil water potential and crop yield.

To obtain integrated values of soil water potential by method II, calculations were performed following the procedure proposed by Taylor (1952). The procedure was theoretically based on the assumption that soil water potential is a continuous function of both depth and time. The application of theory to field data has been accomplished by statistically fitting a linear regression curve to a number of soil water potential readings taken at different depths in the root zone and at different times during the growing season. The coefficients and equations of these curves were then integrated into a single value for the solution. As a first approximation, the first order polynomial was assumed, i.e. the soil water potential was linearly related to depth and time.

The integrated values of soil water potential obtained from method III (Karamanos, 1980) were calculated for four periods during the growing season, i.e. 20, 40, 60, and 75 days after planting. These results were then averaged for the whole growing season so that they were comparable with results obtained from other methods. To use this method,

soil water potential at different depths and soil water depletion rate were required. The soil water depletion was determined for each period between two samplings and the rate of depletion at a particular sampling was taken as the average depletion for two successive time intervals. The difference of soil water content taken shortly after a given irrigation and then 2 days later before the next irrigation provides an estimate of water withdrawn from the soil profile (about 0-60 cm depth) by root uptake and evaporation. However, the use of the rate of soil water depletion ($\Delta\theta/\Delta t$) at a given depth as the weighting criterion for the calculation of integrated values of soil water potential was based on the assumption that $\Delta\theta/\Delta t$ was mainly determined by root uptake at that depth. This assumption is not always true since vertical soil water movement is also known to occur (Karamanos, 1980). It should be noted that the values given by method III were integrated values of soil water potential calculated from soil water potential data obtained before the irrigation.

Table 7 Representative values of soil water potential over depths within effective root zone throughout the growing season of sweet corn, obtained by three computation methods.

Treatment	Soil water potential (-cm)		
	Method I (Arithmetic)	Method II (Taylor)	Method III (Karamanos)
A	214	219	258
B	250*	257*	224*
B(wet row)	179	181	171
B(dry row)	320	333	277
C	256**	264**	242**
C(wet row)	168	171	157
C(dry row)	343	358	326

* and ** indicating average values of B(wet row) and B(dry row) for treatment B; and C(wet row) and C(dry row) for treatment C, respectively.

Table 7 presents the values of soil water potential using the three calculation methods. Results for method I and method II are relatively close for all treatments. The use of method III (Karamanos, 1980) resulted in higher values (less negative) as compared to results of the other two methods. This can be partially explained by the method of calculation: the soil water depletion rates were calculated for particular depths within the root zone, i.e. 15, 30, 45, and 60 cm depths for this case. However, the water loss by both evaporation and root uptake from the layer above the 15 cm depth contributed a considerable amount of water loss. This likely resulted in a lower estimated water depletion rate and, consequently an

overestimation (i.e. less negative value of soil water potential). According to Karamanos (1980) it is acceptable to use the water depletion rate ($\Delta\theta/\Delta t$) for weighting in the calculation of integrated soil water potential. This assumption is, however, not valid for a period soon after irrigating when downward water movement together with rapid direct evaporation from the top soil layer may mask to a considerable extent the yield-affecting estimates of integrated soil water potential. Upward water flow usually occurs after the cessation of drainage in parallel with water extraction by plant roots (Ogata et al., 1960; Arya et al., 1975; Stone and Horton, 1975). This may also affect the calculation of soil water depletion rate for a period between two samplings.

The integrated values of soil water potential using simple averaging (method I) and the method proposed by Taylor (method II) as given in table 7 were highly correlated with yield parameters of sweet corn, including leaf area index and plant height. The coefficient of correlation (r) indicated that using method I and method II for integrating soil water potential, as related to crop response, provided better results than the use of method III, although r values for the Karamanos method also show a reasonable correlation.

Table 8 Correlations of representative values of soil water potential using three different methods and yield parameters of sweet corn.

Yield parameters (g/m ²)	Methods of integrating soil water potential		
	I (Simple)	II (Taylor)	III (Karamanos)
	----- coefficient of correlation (r) -----		
Plant fresh weight	0.897	0.895	0.803
Ear fresh weight	0.973	0.972	0.920
Total fresh weight	0.935	0.933	0.858
Plant dry weight	0.928	0.927	0.840
Ear dry weight	0.975	0.957	0.898
Total dry weight	0.958	0.957	0.898
Leaf area index	0.938	0.938	0.832
Plant height (cm)	0.972	0.972	0.930

The correlation analysis which resulted in Table 8 data was based on integrated values of soil water potential presented in table 7 and average yield parameters of treatments A, B(wet and dry rows) and C(wet and dry rows) with no replications. Replication of data in Table 7 was not possible because of the lack of replicated soil water depletion data required by method III.

Table 9 Correlations of soil water potential calculated for particular growth periods and some yield parameters of sweet corn at different growth periods.

Growth period	Yield parameters		
	Total fresh wt (g/m ²)	Total dry wt	LAI
	r		
2*	0.875	0.891	0.863
3*	0.767	0.716	0.855
4*	0.673	0.644	0.736
2 and 3**	0.857	0.775	0.896
3 and 4**	0.718	0.783	0.669
2, 3 and 4***	0.654	0.703	0.674
All****	0.832	0.847	0.914

* Based on averaged soil water potential and yield at particular growth period.

** Based on averaged soil water potential and yield of the second and third growth periods.

*** Based on averaged soil water potential during indicated growth periods and yield at maturity.

**** Based on averaged soil water potential throughout the growing season and yield at maturity.

Correlations of soil water potential and some yield parameters of sweet corn were also computed for particular growth periods (Table 9). Representative values of soil water potential obtained by method I (simple averaging) for particular growth periods are also given in Appendix D. Yield parameters of total fresh weight, total dry weight (total dry matter production) and leaf area index (LAI) for different growth periods are provided in Appendix E for all

treatments. Method I was used for calculating representative values of soil water potential for Table 9 correlations because it is the simplest method and gives reasonable results which are similar to those obtained by method II. The first growth period is not included in Table 10, since it was a period before the treatments started (20 days after planting). Table 9 shows that the highest correlation coefficient (r) value was obtained during the second growth period (20 to 40 days after plantings) of nearly full vegetative development. The combination of second and third growth periods also provided a good correlation, whereas the fourth growth period (60 to 75 days after planting) gave a poor correlation between soil water potential calculated for that particular period and yield parameters at maturity. This may be due to the influence of rain (4.5 cm) at the beginning of the fourth growth period. A good correlation was also obtained by the representative value of soil water potential calculated for the whole growing season and yield at maturity.

Method I and method II gave similar results of integrated soil water potential values and good correlations with crop yield. Therefore, method I is both adequate and simple. The representative values of soil water potential for the whole growing season obtained by method I (simple averaging) are shown in Figure 19. These values were averaged over different depths and over time for all

treatments. Note that treatments B and C were split into wet rows (with drip lines) and dry rows (without drip lines). The relationship of representative (average) soil water potential using the simple averaging method and some yield parameters of sweet corn at maturity were additionally presented in Figures 20 and 21. It should be noted that the statistical analysis was performed between crop yield and soil water potential values (averaging over depths and time) for particular crop rows where yield data were obtained. This was done when wet and dry rows (with and without drip lines) were considered in treatments B and C. The representative values of soil water potential (averaging over all depths, lateral distances and over time) were correlated with overall yield obtained from harvested areas. Figure 20 shows that marketable ear yield of wet rows obviously differed from those of dry rows, but there were no appreciable differences in yield among wet rows of all treatments. The overall ear yields of the three treatments (narrow solid bars) also show that the yield decreased as spacing of line source increased.

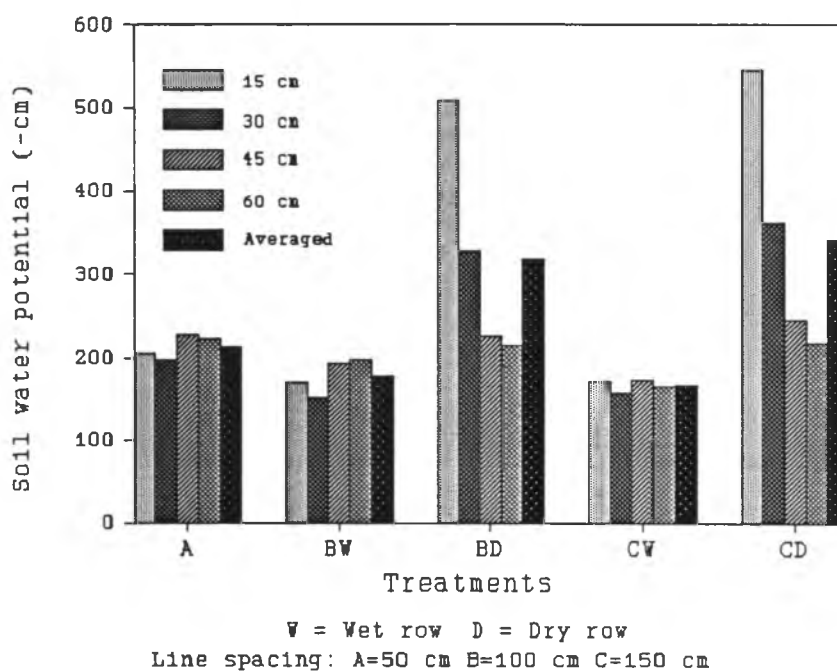


Figure 19 Soil water potential at different depths and integrated values throughout the growing season for different treatments: A, B(wet), B(dry), C(wet), and C(dry).

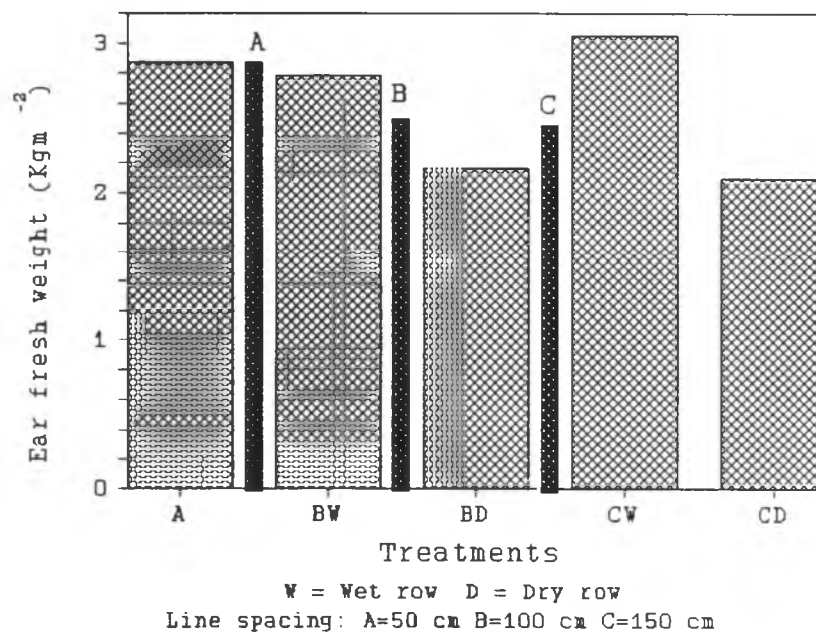


Figure 20 Marketable ear yield of sweet corn for various line spacings. The solid bars represent average of wet and dry rows of treatments B and C.

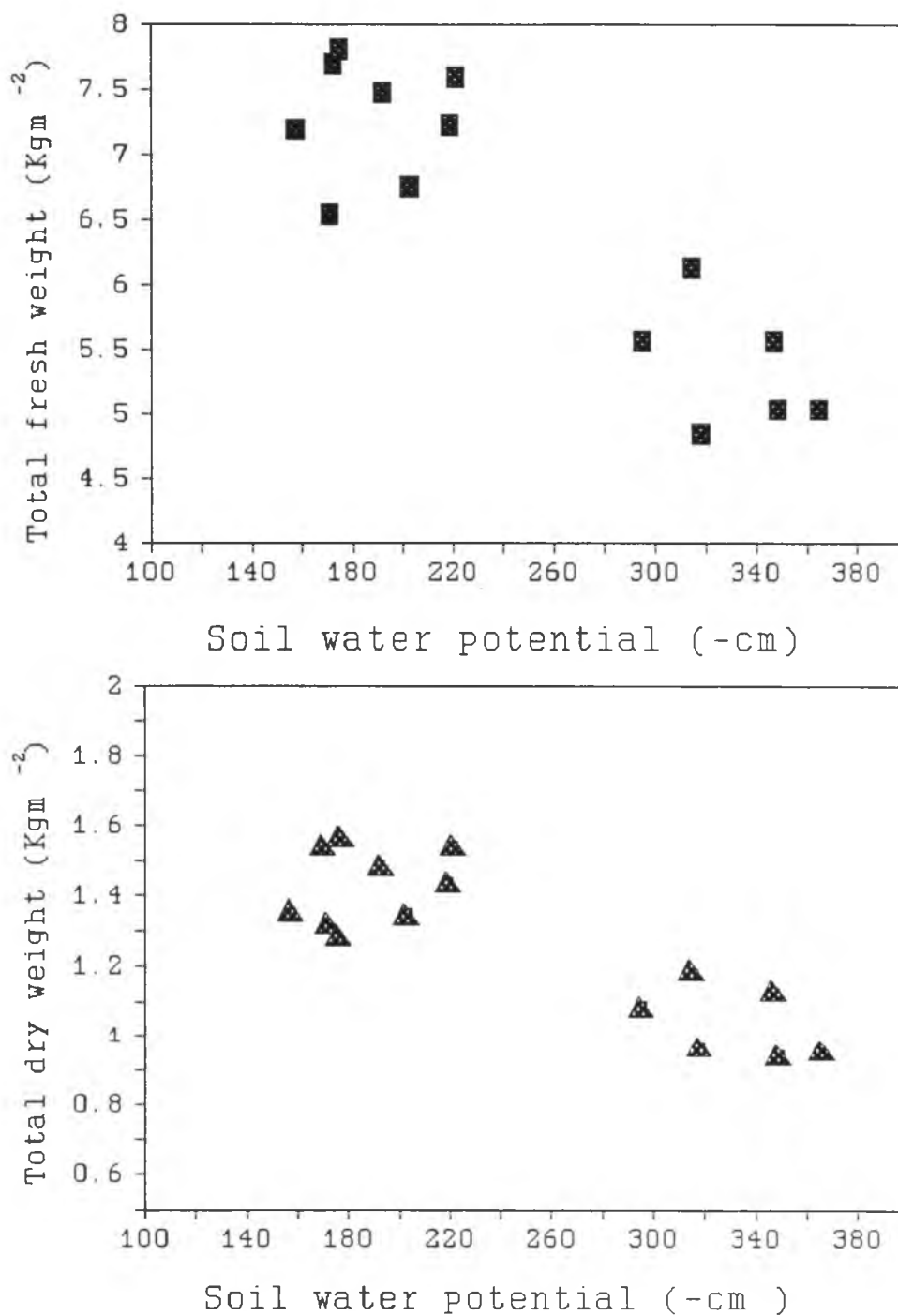


Figure 21 The relationship of sweet corn yield as total fresh and total dry matter production versus vertically integrated soil water potential throughout the growing season.

Data in Figures 20 to 21 show a clear yield response to representative (average) values of soil water potential over all depths throughout the growing season. The yields generally decreased as the average soil water potential values decreased (more negative). These data suggest that representing values of soil water potential by means of integrating or averaging soil water potential for the effective root zone of the crop provides basic information on crop response to soil water. This technique has been used successfully in several previous studies (Philip and Gardner, 1960; Denmead and Shaw, 1962; Arya et al., 1975). It should also be pointed out that the methods used for relating crop response to soil water potential under field conditions may vary in their adequacy due to spatial and temporal variation of crop development and water conditions in soils. Validation of the method used is difficult to accomplish, although many studies have shown that crop yield is strongly related to the energy status of water and thus to the soil water potential. It is important to maintain the soil water potential within a given range for optimal crop production (Kramer, 1983). For practical reasons, this study suggests that the arithmetical integration (method I) is simple and adequate to obtain representative values of soil water potential in relation to crop response.

4.2.4 Soil Water Potential Midway Between Line Sources versus Crop Yield

Soil water potential midway between sources (emitters or line sources) has been referred to as h_c (Bresler, 1978) or as h_m (Warrick et al., 1979). This value has been used as a reference point or as one of the parameters in soil water flow models for drip irrigation system design and operation, especially in the design of emitter spacing and discharge. The h_c value can be viewed as the critical soil water potential according to crop water requirement. Midway between sources (either point source or line source) is a suitable location for recognizing the overlapping of wetted zones or a boundary of the wetting front. The driest point in the profile under drip irrigation is normally at the surface midway between the sources (Warrick et al., 1979). It was also found in our field study that zones of dry soil with lower values (more negative) of soil water potential were developed midway between line sources.

The selection of the h_c value to be used in drip irrigation design depends on both the soil hydraulic properties and on the crop of interest; this value is somewhat arbitrary because of the uncertainty involved in the response of plants to partially wetted soil volumes (Bresler, 1978). In addition, its direct physical significance to crop response is questionable (Russo, 1984). Deterministic modeling of crop response in relation to h_c is difficult, due in part to variation in soil water potential

in both space and time as well as the dynamic change of a particular crop throughout the growing season. The selection of h_c value requires knowledge of crop response to size and shape of wetted soil volume and to water distribution and fluctuation within this volume. Since crop yield is directly related to the soil water regime, the use of h_c value in drip system design will affect the distribution patterns of soil water potential which, in turn, may affect the crop yield.

Measured data of soil water potentials midway between the sources versus time are presented in section 4.1.2. The greatest variation in h_c values was recorded near the soil surface. The variation decreased at lower depths, especially at depths below 45 cm. The values of soil water potential midway between line sources of the second, third and fourth growth periods are given in Table 10 for different depths. The soil water potential values of the fourth growth period were higher (less negative) than those values of the third period. This is probably due to the effect of rain (202 Julian day) at the beginning of the fourth growth period. Generally, the h_c values decreased (more negative) as spacing between sources increased (Table 10). Russo (1983, 1984) found that for a given discharge rate, the increase of spacing between emitters reduced the average h_c and average yield of Bell pepper, and increased the variance of both h_c and yield.

Table 10 Soil Water Potential midway between line sources (-cm) of different treatments (50, 100 and 150 cm spacings) at five different depths for different growth periods.

Spacing Treatment	Growth period	Depths (cm)				
		At surface (5)	15	30	45	60
A(50)	2	201	193	169	160	159
	3	246	218	283	268	304
	4	309	251	240	243	232
	mean 1 to 4	252*	221*	230*	223*	231*
B(100)	2	508	350	174	162	156
	3	571	690	476	297	291
	4	558	537	378	245	216
	mean 1 to 4	546*	527*	343*	234*	221*
C(150)	2	553	358	168	145	147
	3	825	813	655	404	341
	4	591	574	394	285	232
	mean 1 to 4	656*	581*	407*	278*	240*

* average values throughout the growing season

Table 11 Correlations of soil water potential midway between sources calculated for particular growth periods and some yield parameters of sweet corn at different growth periods (n = 9).

Growth period	Yield parameters (g/m ²)		
	Total fresh wt	Total dry wt	LAI
	r		
	at surface		
2	0.87	0.86	0.94
3	0.80	0.78	0.86
4	0.66	0.73	0.92
All	0.87	0.79	0.94
	at 15 cm depth		
2	0.87	0.86	0.91
3	0.94	0.89	0.97
4	0.87	0.82	0.89
All	0.90	0.93	0.95

Table 12 The relationship between the soil water potential midway between line source (h_c) at different depths and yield parameters of sweet corn, as indicated by the coefficient of correlation (r).

Depth (cm)	Yield parameters (g/m ²)						
	Plant fresh wt.	Ear fresh wt.	Total fresh wt.	Plant dry wt.	Ear dry wt.	Total dry wt.	Leaf area index
Surface	0.82	0.81	0.87	0.81	0.68	0.79	0.94
15	0.87	0.81	0.90	0.95	0.82	0.93	0.96
30	0.52	0.42	0.52	0.61	0.52	0.59	0.77
45	0.00	0.10	0.00	0.14	0.30	0.22	0.24
60	0.00	0.00	0.00	0.00	0.10	0.00	0.00

Soil water potential midway between line sources (h_c) at different growth periods were correlated with some yield parameters. The coefficient of correlation (r) is shown in Table 11 for the h_c measured at the surface (5 cm) and the 15-cm depth. The second and third growth periods gave higher r values than that of the fourth growth period.

Table 12 shows a correlation analysis of seasonal-averaged soil water potential midway between sources (measured h_c) and yield parameters of sweet corn at maturity. The coefficient of correlation (r) indicates that the h_c values at 15 cm gave the highest correlation between the h_c and yield parameters of sweet corn, and the correlation decreased with depth. This can be explained in part by the fact that variation of h_c at lower depth (45 and 60 cm) was small, whereas yield parameters showed

significant differences among treatments. As a result, the coefficient of correlation (r) was markedly low for h_c values at lower depth. Measurement of h_c at or near the surface using tensiometer was practically difficult under field conditions due to air entry in porous cub when soil water potential dropped below about -800 cm of water. These tensiometers required special attention almost daily. Therefore, it is suggested that the h_c value at the 15-cm depth is the preferred indicator of crop response, as compared to h_c values at other depths. The results from this study indicate that a single value of h_c can be estimated from experiments for individual crops. For sweet corn, the h_c value at 15 cm depth was about -220 cm, and about -250 cm for the h_c value defined at the soil surface.

Figures 22 to 25 show that yields of sweet corn, in terms of total fresh and dry matter production, decreased as the soil water potential midway between line sources decreased (more negative). This relationship is also well defined with increasing soil depths, as indicated by decreasing of r^2 values (coefficient of determination). The h_c values at 45 and 60 cm depths showed no relationship with the yield of sweet corn ($r^2 < 0.05$).

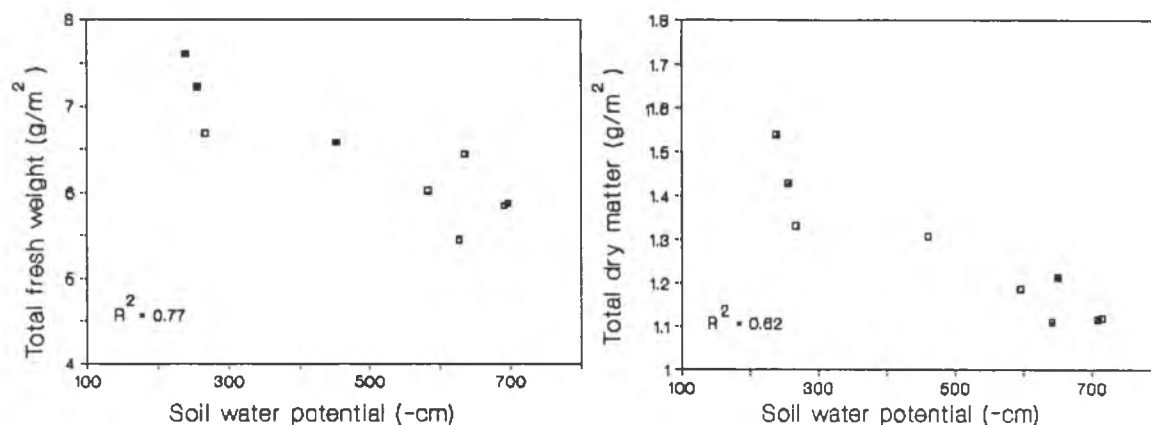


Figure 22 The relationship between soil water potential at the soil surface midway between line source and yield of sweet corn.

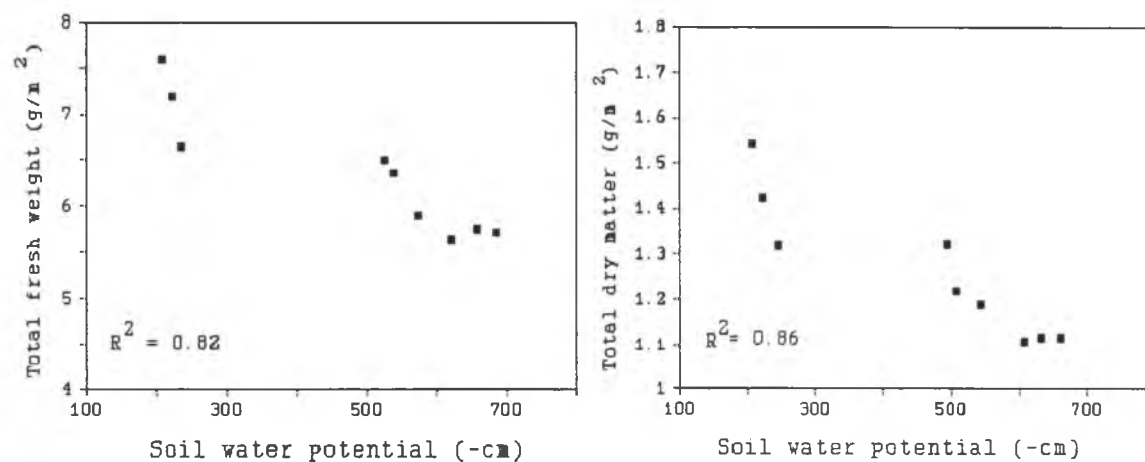


Figure 23 The relationship between soil water potential at 15 cm depth midway between line source and yield of sweet corn.

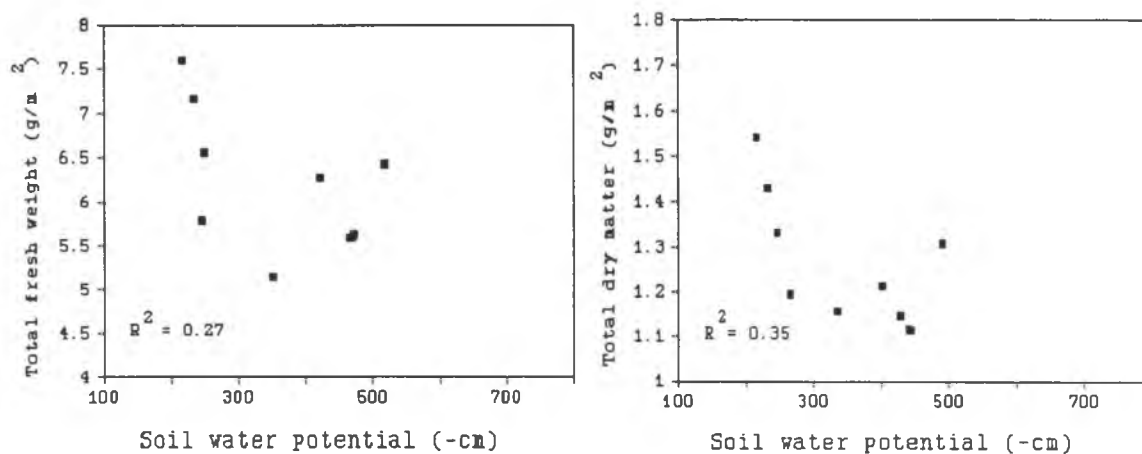


Figure 24 The relationship between soil water potential at 30 cm depth midway between line source and yield of sweet corn.

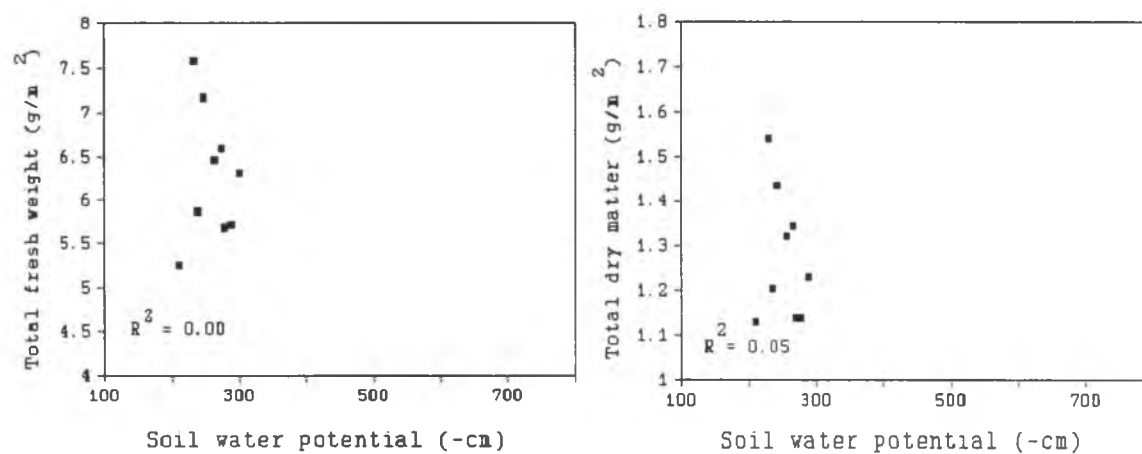


Figure 25 The relationship between soil water potential at 45 cm depth midway between line source and yield of sweet corn.

According to Russo (1984), the dependence of yield on h_c decreased with time due to root growth which increased the soil volume to which the plants responded. Thus, it seems that the concept of midway soil water potential on which the drip irrigation design problem (Bresler, 1978) is based, is important in the early stage of plant growth. The results from this experiment indicate that the highest correlation of h_c and yield was obtained at the second growth period (Table 11).

The results suggest that the seasonal averaged h_c values obtained from this experiment for sweet corn (-220 to -250 cm) was reasonable to be used as a reference point for the soil water potential as related to crop response. Phene and Beale (1976) reported that optimal ear yield of sweet corn was produced with drip irrigation when the soil water potential at 15 cm soil depth was controlled at about -200 cm (-0.2 bar). Generally, the difference in h_c values can be partially explained by the fact that these values are affected by surface evaporation, while crop growth stage (in terms of root water uptake) also plays a very important role in affecting such values. In addition, the irrigation system (in term of spacings of line sources, discharge rate, the total amount of water applied and soil hydraulic properties strongly influenced the h_c value. It is generally accepted that horizontal soil moisture movement can be increased by increasing the discharge rate (Bresler,

1978; Schwartzman and Zur, 1986). The shape of wetted zones strongly depends on soil capillary forces as well as gravity. To achieve the higher (less negative) h_c value by increasing horizontal distribution, the vertical distribution should not be significantly affected, to avoid water loss beneath the root zone. The use of a high h_c value (less negative) in drip irrigation system design will result in a closer spacing, while a low h_c value (more negative) will result in a wider spacing. It was observed in this experiment that a good uniformity of irrigation water was obtained with close spacing of line sources rather than with wide spacings.

4.3 Model Application and Results

Two- and three- dimensional flow models from point or line sources with or without water extraction were developed by Warrick et.al. (1979,1981) but have not been tested under field conditions. Computer programs were also written in FORTRAN along with the manual (1981) to allow easy application for available solutions. Parts of these programs were further modified for two-dimensional (2-D) flow from line sources with different root uptake patterns (Warrick,1990). This modified program (TWO.FOR) was applied and evaluated in this study that combines a row crop (sweet corn) and line sources within a field experiment. The experimental data for comparison are usually more easily obtained in the 2-D rather than 3-D case, especially under field crop conditions.

Although this model can be applied to both steady-state and time-dependent cases, only the steady-state case was emphasized and evaluated. This was done to simplify and to eliminate an ambiguous assumption that change in soil hydraulic conductivity with respect to water content is constant, which is needed for the time-dependent case.

In order to use this program, all parameters required must be known or specified in the data input file 'TWO.SPE'. The output goes to a file 'TWO.OUT', which contains statements of data input and tables of SWP expressed in soil water pressure heads. In addition, the pressure heads are

given in column format in a file 'TWO.COL' that can be easily transferred to other commercial programs for further analyses.

The data input or parameters used in the model are as followed:

System parameter

NX Number of X coordinates (unit : cm)

Trt A : 1, 12, 25, 37, 49

Trt B : 1, 17, 34, 40, 50

Trt C : 1, 15, 25, 50, 75

NZ Number of Z coordinates (unit : cm)

Trt A,B,C : 5, 15, 30, 45, 60 (for all Trts)

NT Number of T coordinates (unit : day) for time-dependent case only and use zero for steady-state case.

NLINES Number of line sources

SPCLIN Spacing of line sources

Trt A,B,C : 50, 100, 150 respectively

D Depth of the sources (unit : cm)

use zero for surface source.

QS Strength of source (unit : $\text{cm}^2 \text{ day}^{-1}$).

Growth Period	Trt A	Trt B	Trt C
1	30	60	90
2	32	64	96
3	35	70	105
4	32	64	96

Soil parameters

- ALPHA The α of Eq. $K = K_0 \exp(\alpha h)$ (unit : cm^{-1})
 use averaged value of 0.032 for Molokai soil.
- XKO The empirical constant K_0 (unit : cm day^{-1})
- XLK $dK/d\theta$ assumed constant (k), use only for
 time-dependent case.

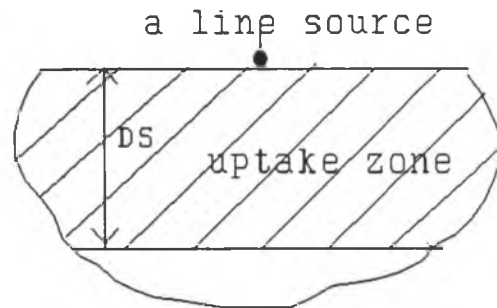
Crop parameters (Refer to Figure 26)

- DS Rooting depth (unit : cm)
 use measured values of 35, 50, 70, 70 for the
 first, second, third and fourth growth periods.
- U The one dimensional uptake rate (unit : cm day^{-1})
- UF The uptake fractions defined as 0.3, 0.4, 0.2, 0.1
 from the surface to the depth of the root zone
 (sum of these fractions must be equal to one).

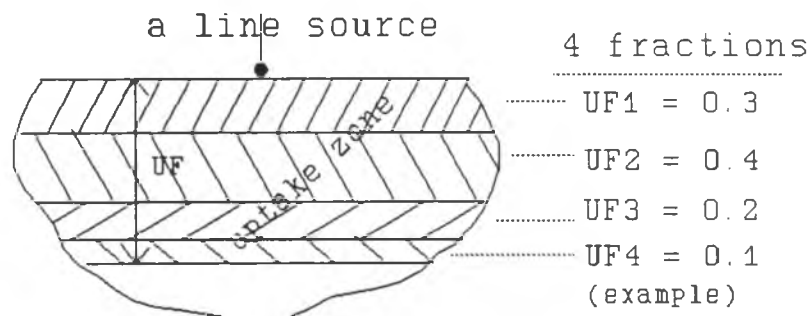
Strip Sink Description (The two dimensional uptake)

- XSTRIP The half width of a strip in x direction
 (Refer to Figure 26 as X_1, X_2, \dots, X_n)
- ZSTRIP The depth of a strip from the surface (z)
 (Refer to Figure 26 as Z_1, Z_2, \dots, Z_n)
- SPCSTRIP The spacing between the center of a strip
 to the center of the adjacent strip, normally
 equal to line spacing, SPCLIN.
- NLSTRIP The number of lines of strips defined within
 the root zone (equal to n of X and Z).
- QSTRIP The strength of strip defined
 (unit : $\text{cm day}^{-1} \times \text{spacing in cm} = \text{cm}^2 \text{ day}^{-1}$)

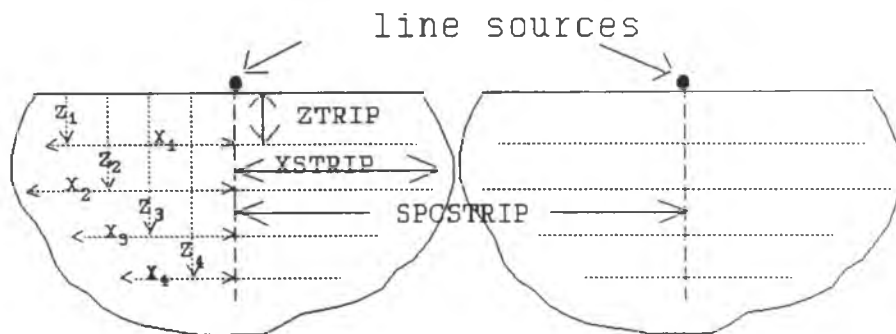
Figure 26 shows examples of possible source-sink combinations with surface line sources and different root uptake patterns.



2-D surface line source with 1-D root uptake



2-D surface line source with fractional uptake



(example : 4 strips)

2-D surface line sources with strip uptake

Figure 26 Geometries of surface line source with different root uptake patterns

The parameters used in the model were based on measured values from the field experiment so that the model results could be comparable to the experimental results. The soil parameters (K_0 and α) of the Molokai soil were obtained from field measurements and the literature. The averaged values for K_0 (59.4 cm day^{-1}) and α (0.032 cm^{-1}) were used for all treatments. The QS (strength of source or discharge rate) was determined according to the amount of water applied, which was estimated from daily pan evaporation. The rates of water applied during the four growth periods were 0.59, 0.63, 0.69 and 0.64 cm day^{-1} yielding an average of 0.64 cm day^{-1} throughout the growing season. The rates of water uptake (U, UF and STRIPS parameters) were determined for the four growth stages based on a pan evaporation method (Doorenbos and Pruitt, 1977) and recommended crop coefficients of 0.7, 1.0, 1.1 and 1.0, giving the water uptake rates of 0.37, 0.53, 0.64 and 0.55 cm day^{-1} for the first, second, third and fourth growth periods respectively. The averaged rate of water uptake was about 0.52 cm day^{-1} .

The required parameters were input at the beginning of the program from a data statement file using solutions for the steady-state case. Model results are presented in Figures 27 to 35 for the four growing periods. The results include simulations with the three geometries of source-sink combinations shown in Figure 26.

Treatment A (50 cm spacing):

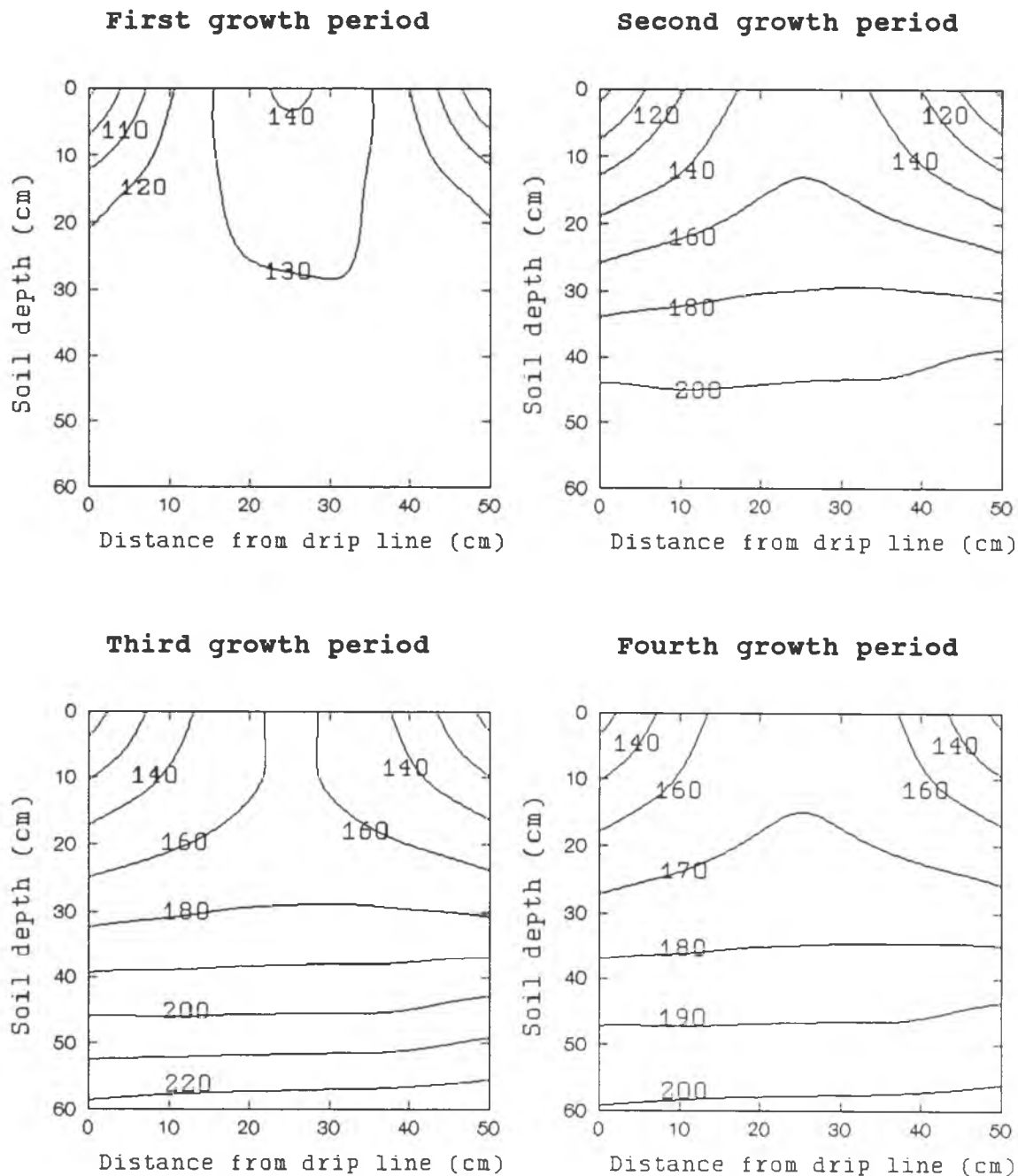


Figure 27 Predictions of soil water potential distributions using the model 'two dimensional linearized moisture flow' with **one dimensional and uniform root uptake** for treatment A during the four growth periods.

Treatment A (50 cm spacing):

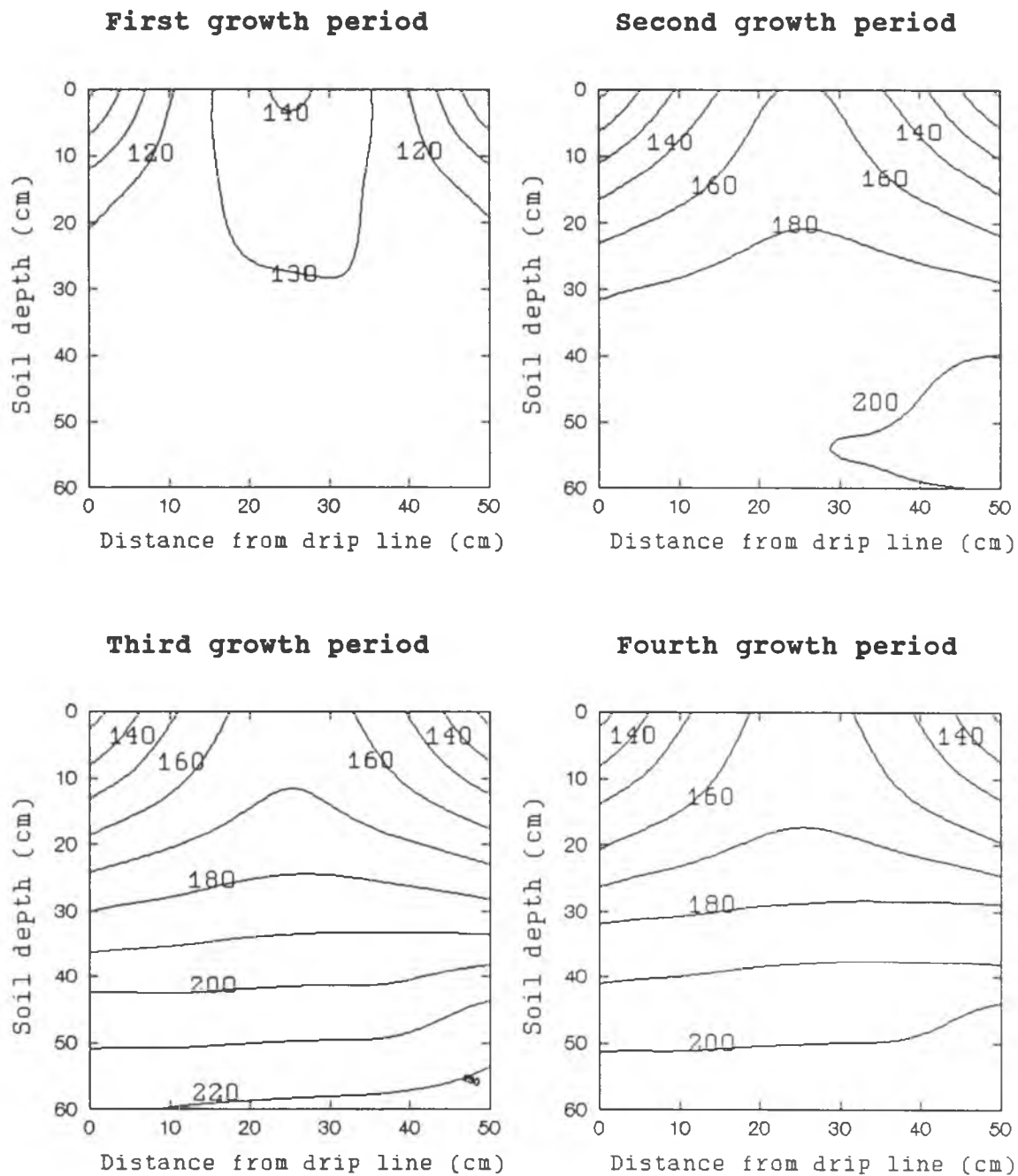


Figure 28 Predictions of soil water potential distributions using the model 'two dimensional linearized moisture flow' with fractional root uptake (one dimensional and uniform within each fraction) for treatment A during the four growth periods.

Treatment A (50 cm spacing):

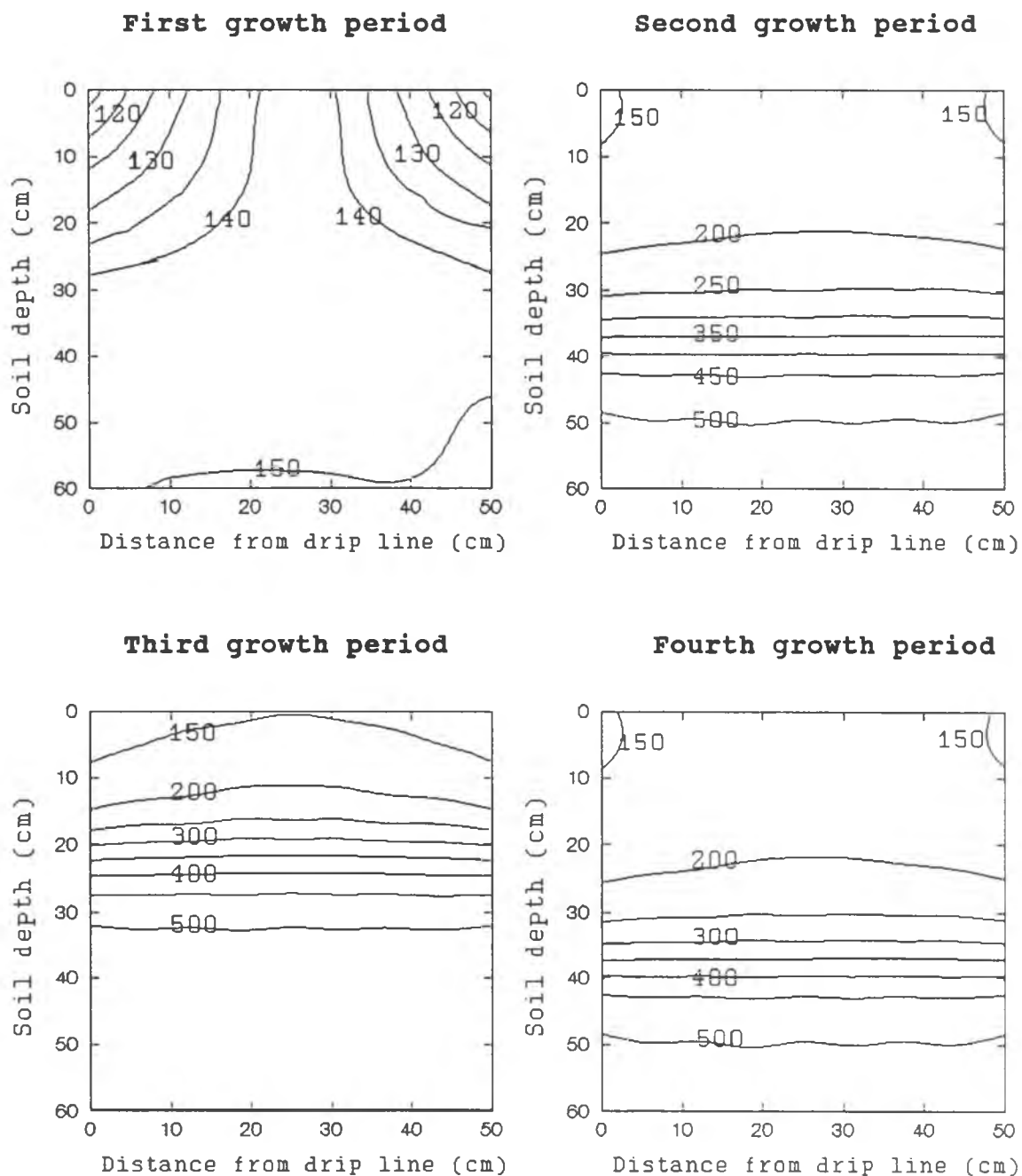


Figure 29 Predictions of soil water potential distributions using the model 'two dimensional linearized moisture flow' with **two dimensional root uptake** (strips) for treatment A during the four growth periods.

Treatment B (100 cm spacing):

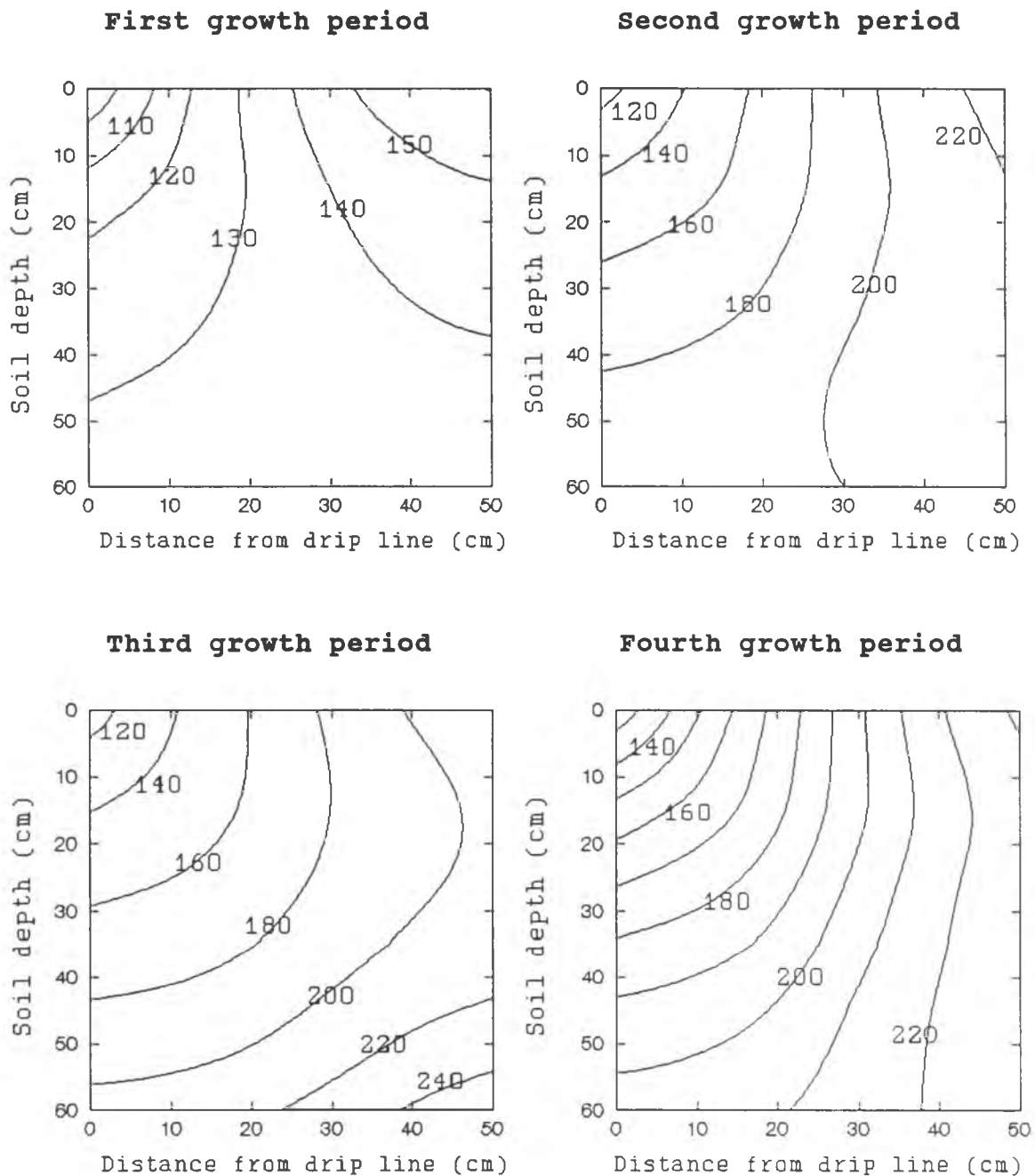


Figure 30 Predictions of soil water potential distributions using the model 'two dimensional linearized moisture flow' with **one dimensional root uptake** for treatment B during the four growing periods.

Treatment B (100 cm spacing):

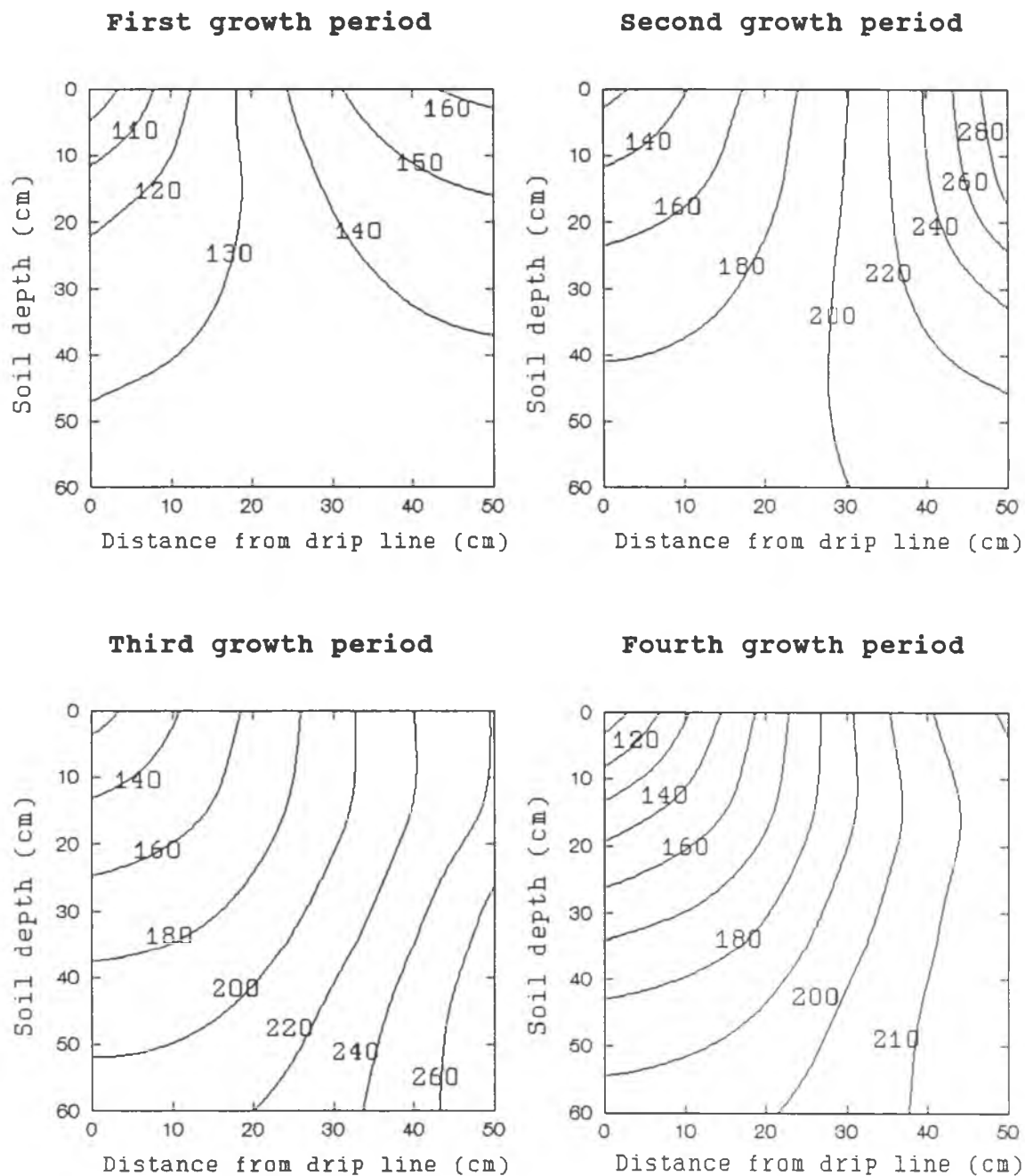


Figure 31 Predictions of soil water potential distributions using the model 'two dimensional linearized moisture flow' with **fractional root uptake** (one dimensional and uniform within each fraction) for treatment B during the four growing periods.

Treatment B (100 cm spacing):

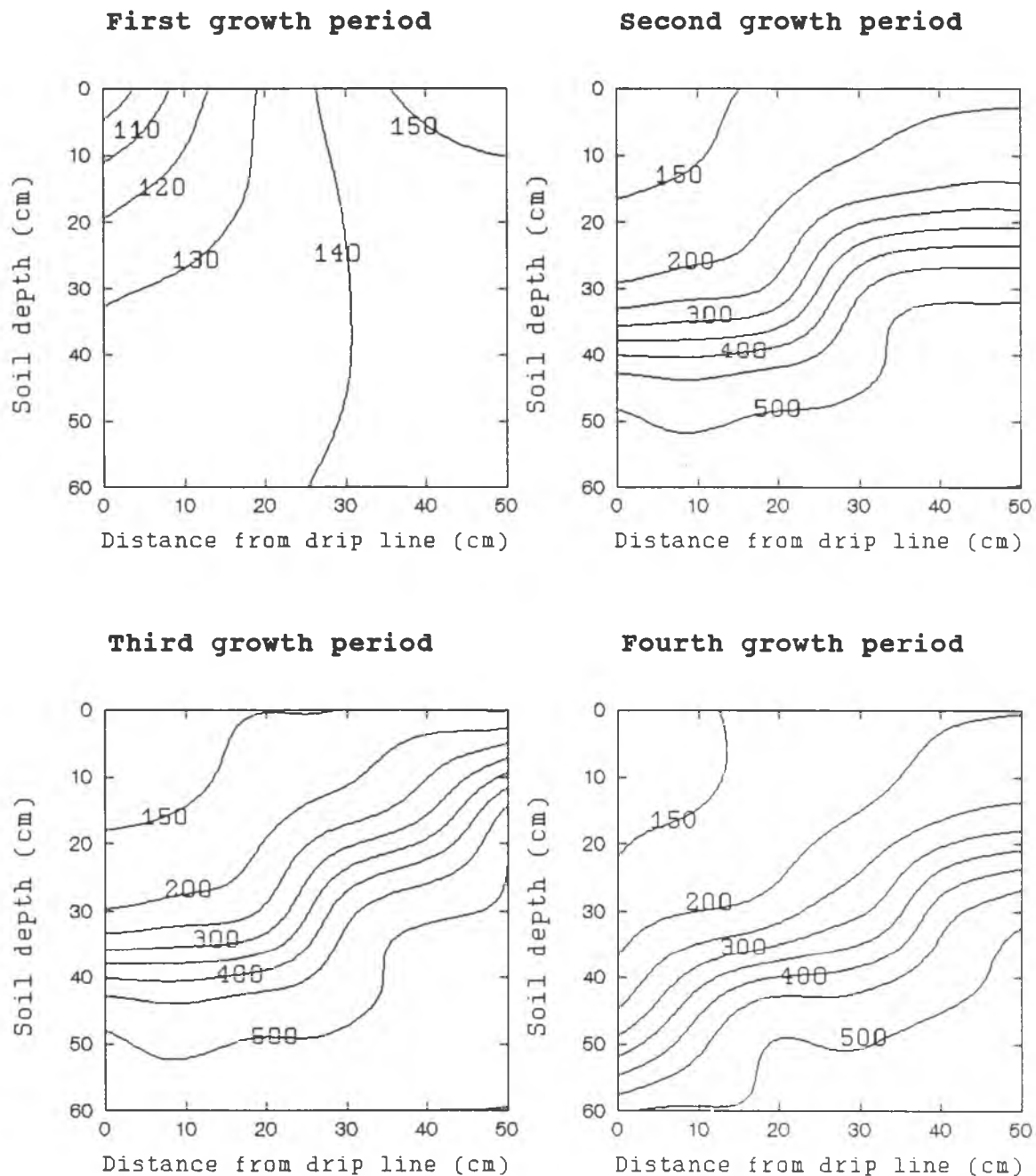


Figure 32 Predictions of soil water potential distributions using the model 'two dimensional linearized moisture flow' with **two dimensional root uptake** (strips) for treatment B during the four growing periods.

Treatment C (150 cm spacing):

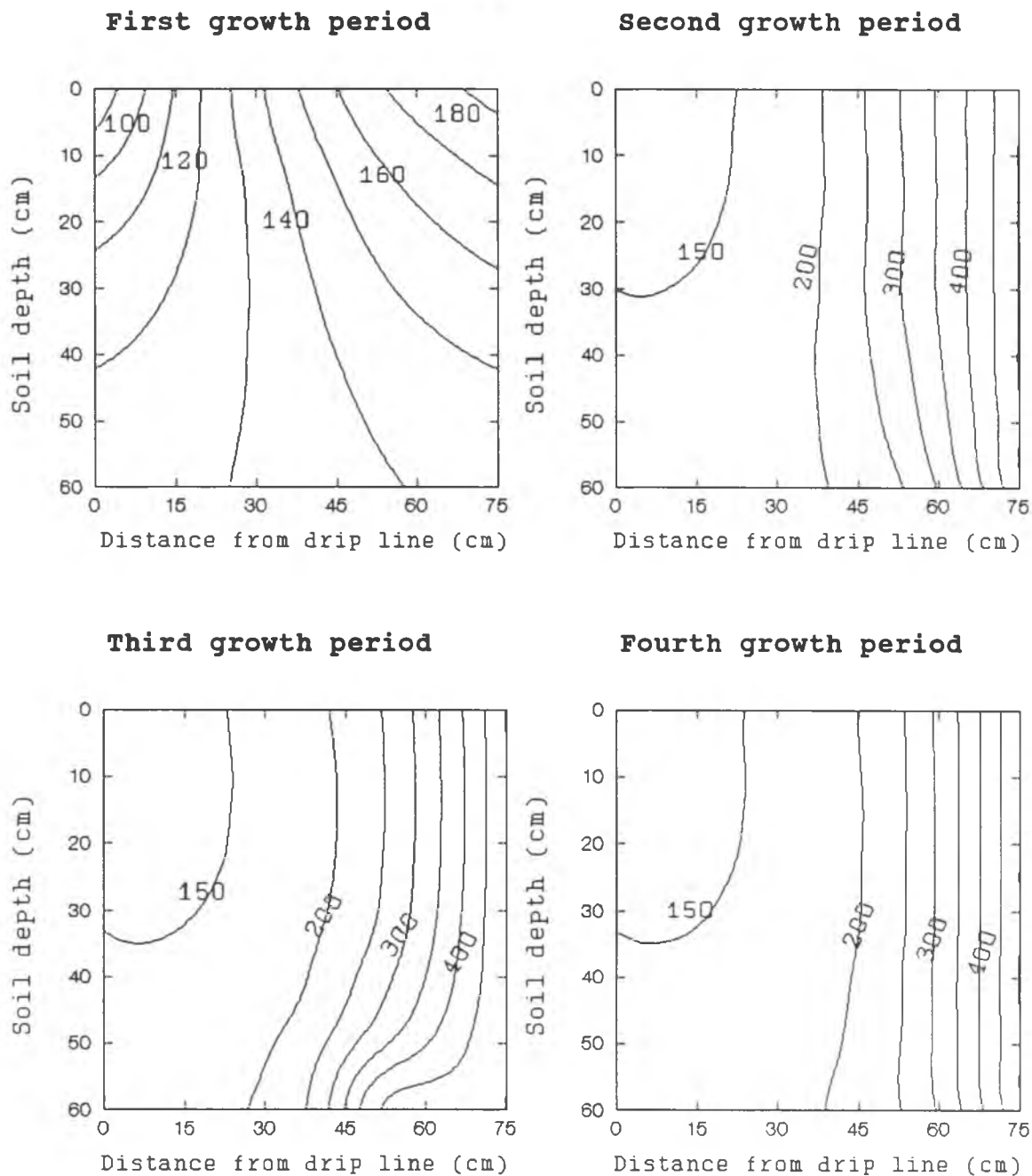


Figure 33 Predictions of soil water potential distributions using the model 'two dimensional linearized moisture flow' with **one dimensional root uptake** for treatment C during the four growing periods.

Treatment C (150 cm spacing):

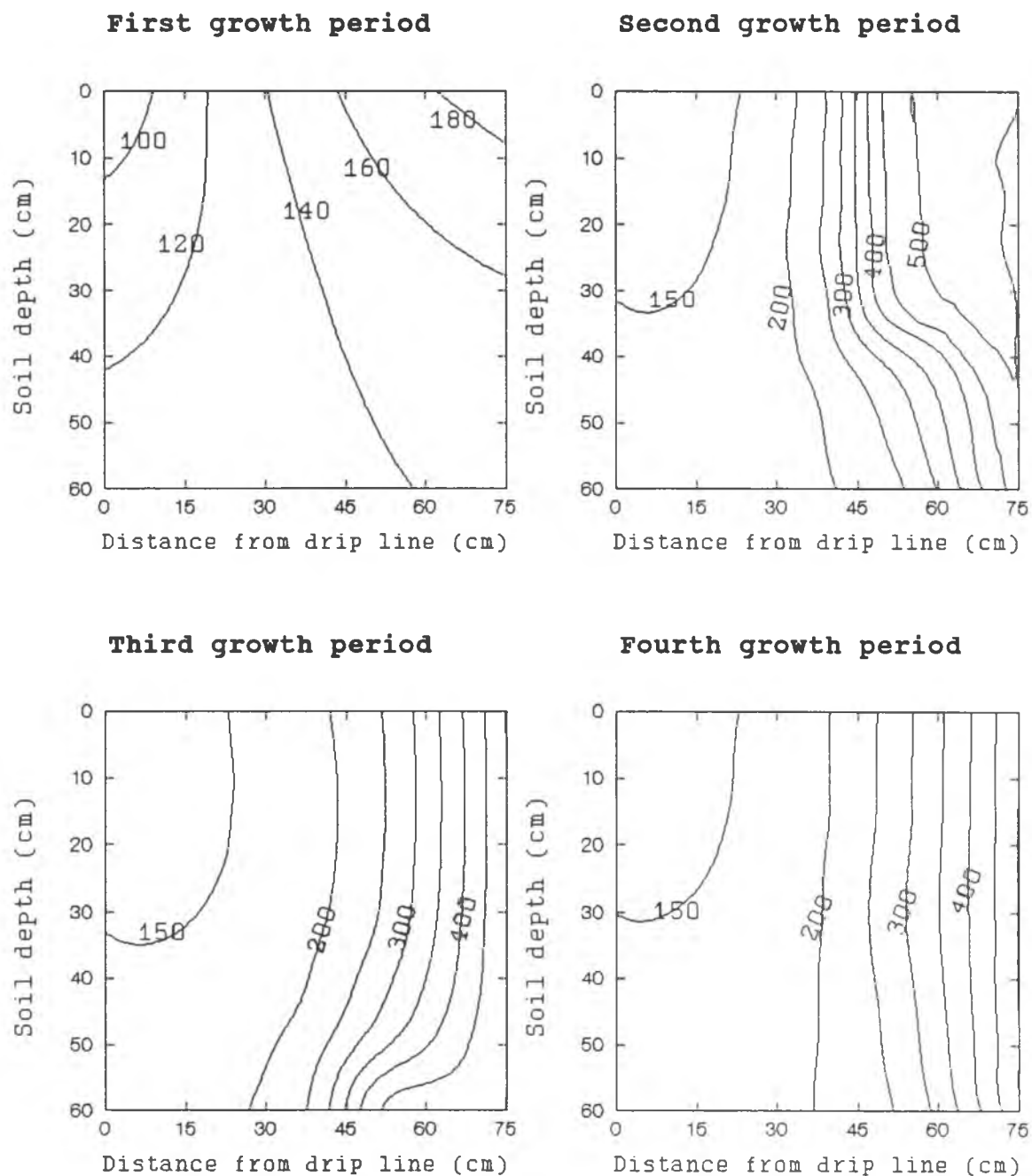


Figure 34 Predictions of soil water potential distributions using the model 'two dimensional linearized moisture flow' with **fractional root uptake** (one dimensional and uniform within each fraction) for treatment C during the four growing periods.

Treatment C (150 cm spacing):

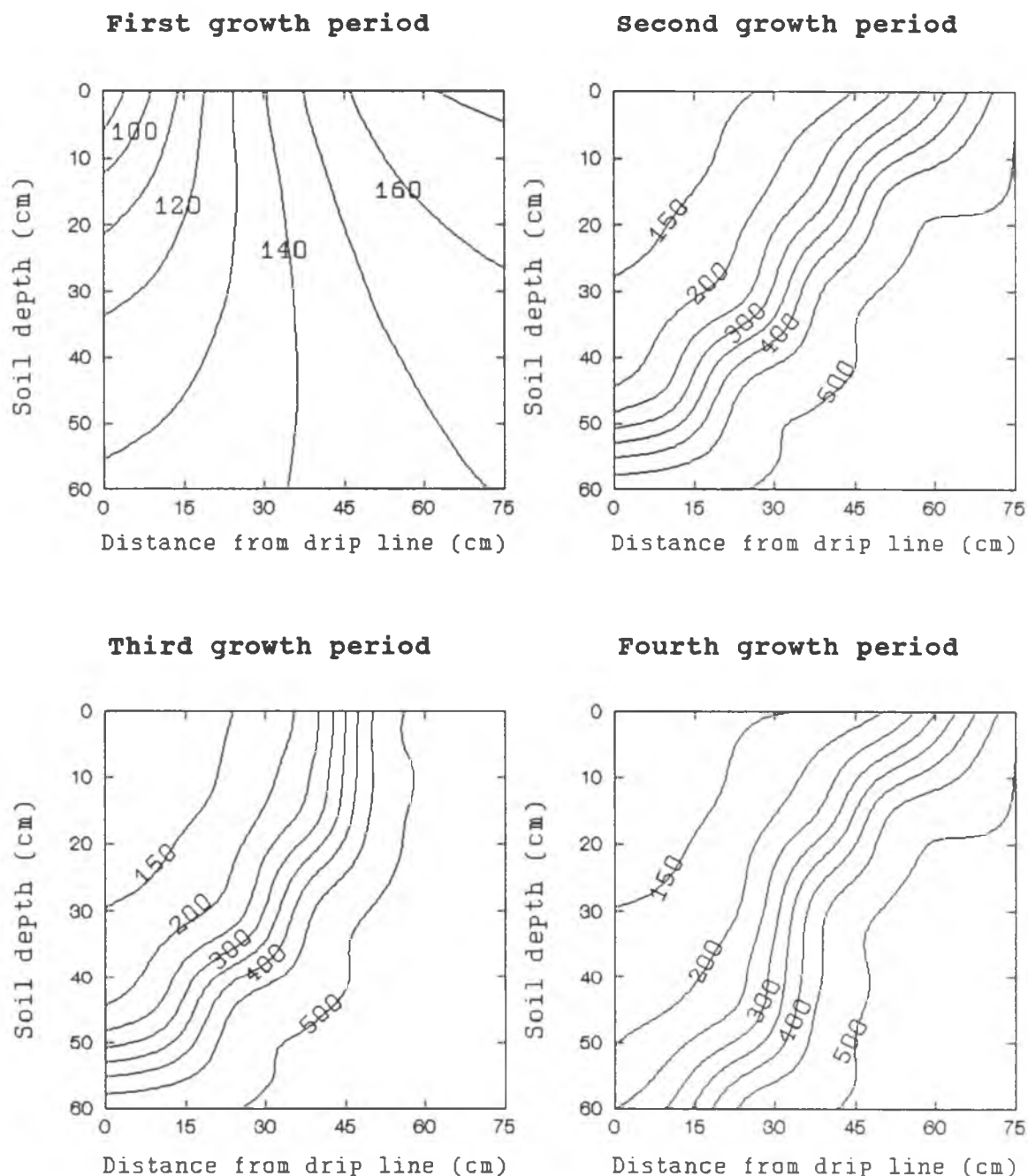


Figure 35 Predictions of soil water potential distributions using the model 'two dimensional linearized moisture flow' with **two dimensional root uptake (strips)** for treatment C during four the growing periods.

These figures show two-dimensional flow patterns from surface line sources with different plant water uptake patterns for the three treatments and the four growth periods. Contours of equal soil water pressure head indicates that there were no appreciable differences in results obtained from one-dimensional uniform uptake (1-D) and fractional uptake for all treatments, whereas strip uptake gave different patterns of SWP distributions.

It should be recognized that SWP distribution patterns of treatment A were developed from two line sources, 50 cm apart, whereas treatments B and C show the SWP distributions up to the midway between the line sources, i.e., 50 and 75 cm respectively. Figures 27 to 29 show that at approximately the 20 cm depth of treatment A, contours of equal SWP formed continuous lines between line sources, and the wetted patterns were similar for one dimensional uptake and fractional uptake with the SWP range of about -120 to -220 cm of water. The similar effects of these two root uptake patterns were also found for Treatments B and C. As previously mentioned, the strip uptake resulted in different SWP distribution patterns with lower range (more negative) SWP values of -150 to -500 cm. This demonstrates that possibly the strip uptake function used in the model calculation tends to give an over estimation (more negative values) of water uptake by roots. This is confirmed by the field results, to be discussed later.

Figures 30 to 32 show somewhat bulb shapes of SWP distribution patterns near the line sources of treatment B (100 cm spacing). The range of SWP throughout the growing season is about -100 to -260 cm. Similar to that of treatment A, the strip uptake yielded lower (more negative) values of SWP and different wetted patterns as compared with results from one dimensional and fractional uptake.

The SWP distribution patterns of treatment C (150 cm spacing) are somewhat oval shaped directly below the line sources as shown in Figures 33 to 35. This implies that the vertical flow is relatively greater than the horizontal flow for the higher amount of water applied per unit line length. The soil is wetter near and below the line sources in comparison to the soil of treatments A and B, but the soil appears drier at distances farther away from the line sources. The seasonal SWP ranges from -90 to -500 cm. The SWP value of -500 cm is used to indicate that water is being withdrawn where none is available in the soil which, of course, is in violation of the real situation (Warrick, 1981 and from personal discussion with Dr. Warrick during February, 1990). Results of treatment C, however, show no differences in SWP values for the first growth period from three different root uptake patterns. However, the strip uptake shows noticeable differences in SWP distribution patterns for the second, third and fourth growth periods.

The results imply that the movement of water through this soil from a line source was influenced by capillary as well as gravitational forces, but the gravitational effects became more pronounced with longer irrigation time, as demonstrated by treatment C. Treatment C required a longer irrigation time than treatments A and B in order to deliver the same amount of water applied per unit area but the highest amount of water applied per unit length due to the smallest total length of line. Phalke (1987) conducted an experiment on this soil and found that the water movement through the soil from a point source appears to be more of a function of volume of water applied than the discharge rate (time).

Generally, the sink term (root uptake function) decreases SWP values, which in turn affect SWP distribution patterns. The results indicate that the strip sink tends to over estimate the soil water potential, as compared with 1-D uniform uptake and 1-D fractional uptake. This may be because the strip sink can be defined in two dimensions (X and Z) and can have as many strips as required within the root zone, i.e $X_1, X_2 \dots X_n$ (XSTRIP) for horizontal direction and $Z_1, Z_2 \dots Z_n$ (ZSTRIP) for vertical direction, where n is the number of strips.

4.4 Comparison of Experimental and Model Results

The SWP data obtained from the field experiment in silty clay soil (Molokai series) were compared with the model results of soil water flow from line source with water extraction as developed by Warrick et.al. (1979,1981). Since the solutions to the steady-state case were used to predict SWP distributions, these results are compared to only the field data taken after irrigation, which more closely to the steady-state condition than the data taken before irrigation. It is recognized that neither of the experiment conditions under which SWP was measured can be considered to represent a steady state. However, data taken after irrigation seem appropriate for model evaluation. This is confirmed by comparisons of results presented in Figures 10, 11 and 12 (experimental results in section 4.1.3) to Figures 27, 30 and 33 (model results in section 4.3) for treatments A, B and C, respectively.

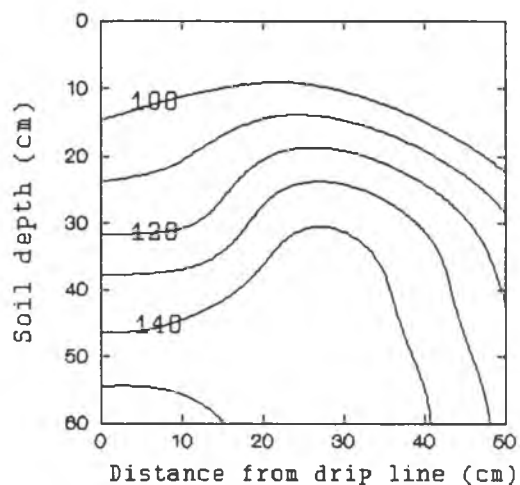
The model results indicated that one-dimensional uniform uptake and fractional uptake (one-dimensional uniform uptake in all fractions) resulted in similar soil water potential values and distribution patterns in comparison with strip uptake (Figures 27 to 35). Thus, the results with one-dimensional uniform uptake were selected to compare with the field results, and presented in more detail. Note that the first period of growth was not considered because the soil was uniformly wet and plant

growth was about the same in all treatments before the treatments started. Relationships of soil water potential and crop yield (section 4.2) suggested that the crop responded significantly to soil water potential during the second and third growth periods, as indicated by the coefficient of correlation. In addition, the soil water potential data (after irrigation) were integrated over the whole growing season and compared with the model results using seasonal averaged parameters of water applied and water uptake (Figure 39).

Treatment A (50 cm spacing):

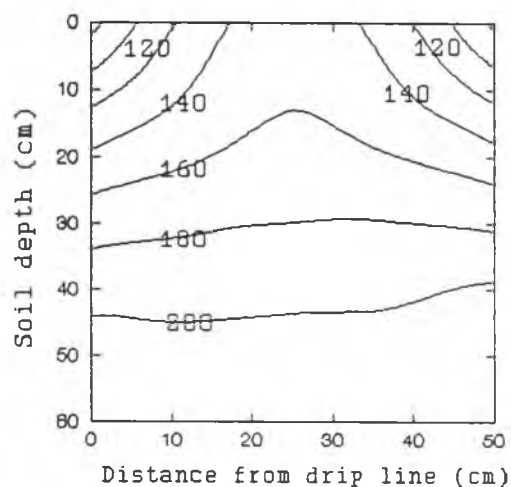
Experimental results

Second growth period

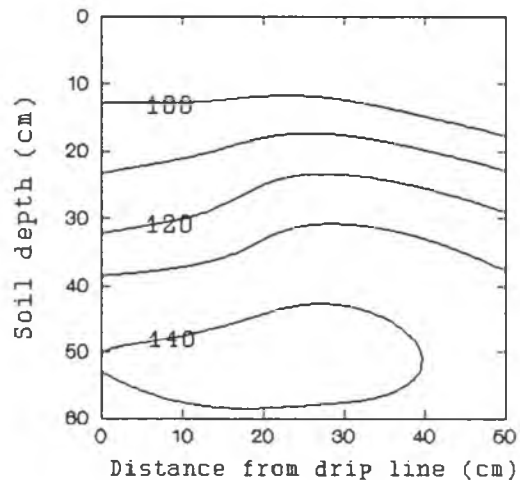


Model results

Second growth period



Third growth period



Third growth period

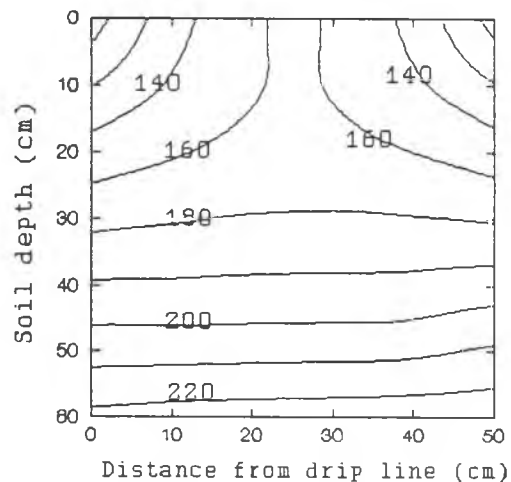
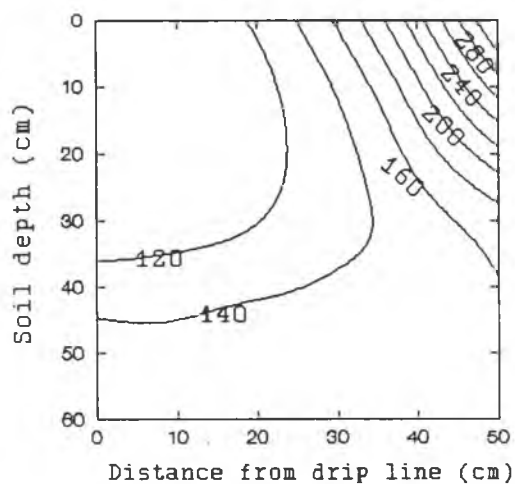


Figure 36 Comparison of soil water potential distributions of treatment A (50 cm spacing) obtained from field experiment and model application for the second and third growth periods of sweet corn.

Treatment B (100 cm spacing):

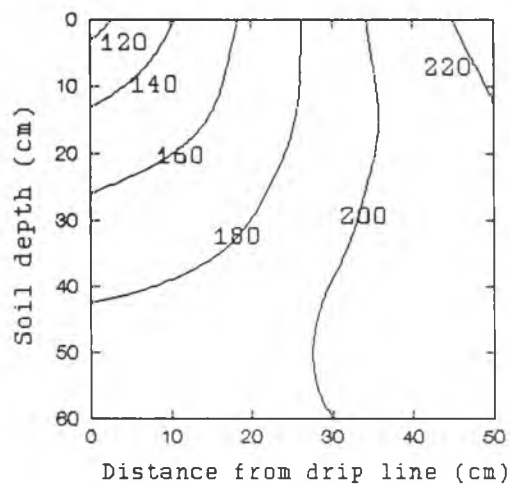
Experimental results

Second growth period

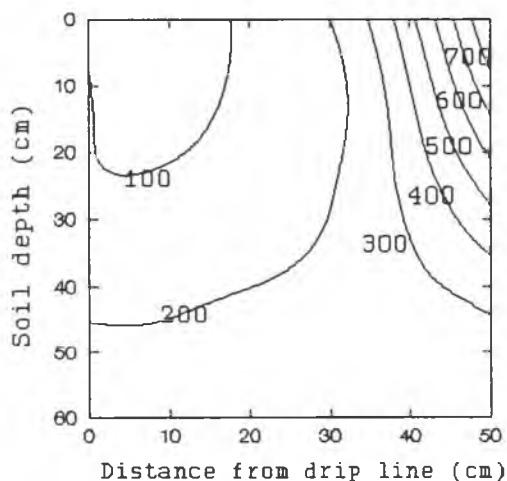


Model results

Second growth period



Third growth period



Third growth period

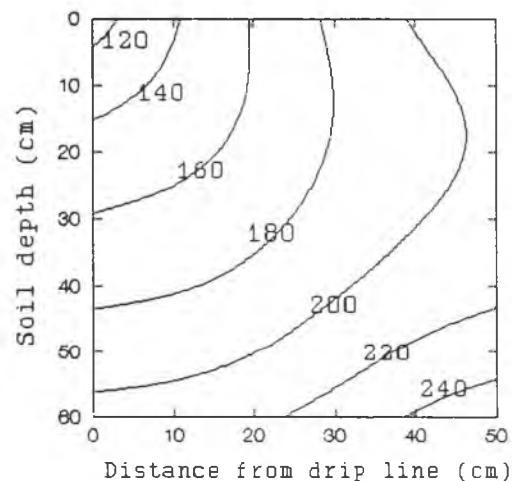
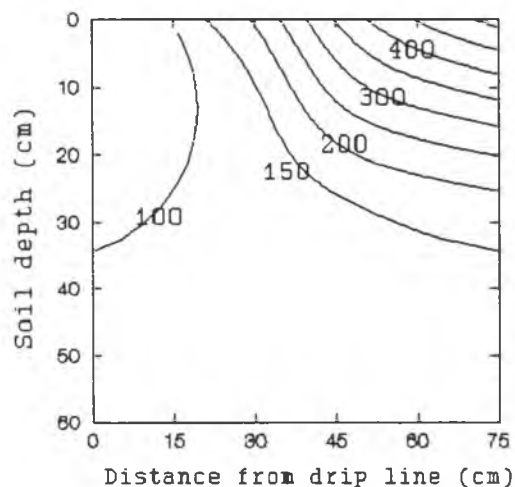


Figure 37 Comparison of soil water potential distributions of treatment B (100 cm spacing) obtained from field experiment and model application for the second and third growth periods of sweet corn.

Treatment C (150 cm spacing):

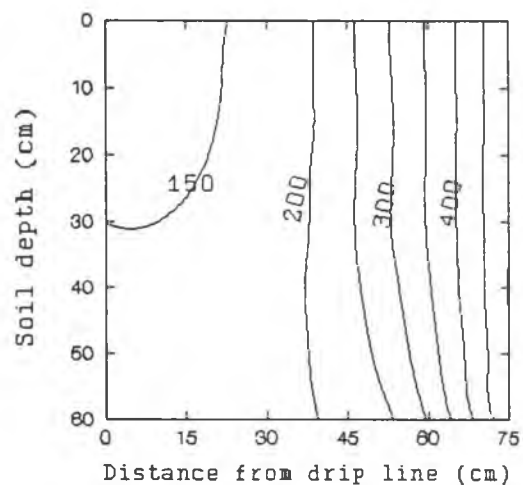
Experimental results

Second growth period

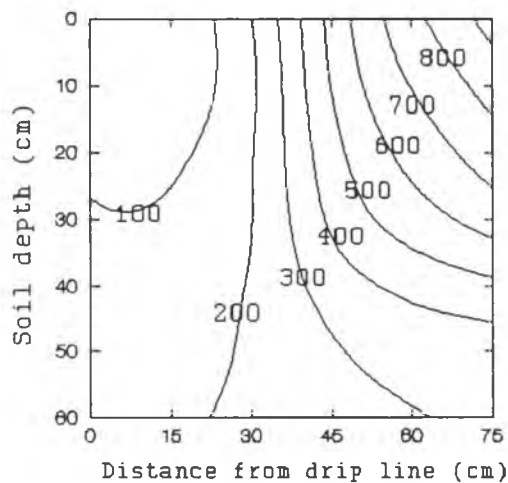


Model results

Second growth period



Third growth period



Third growth period

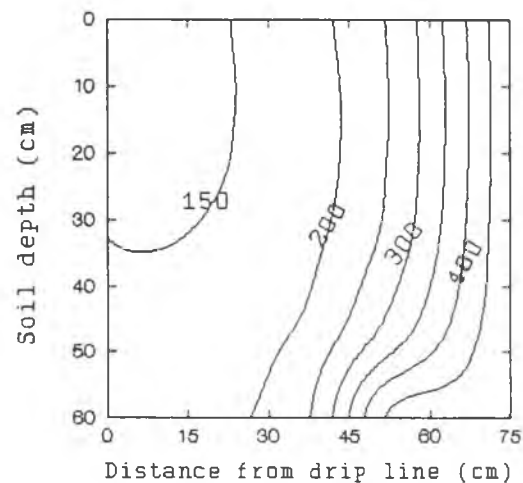
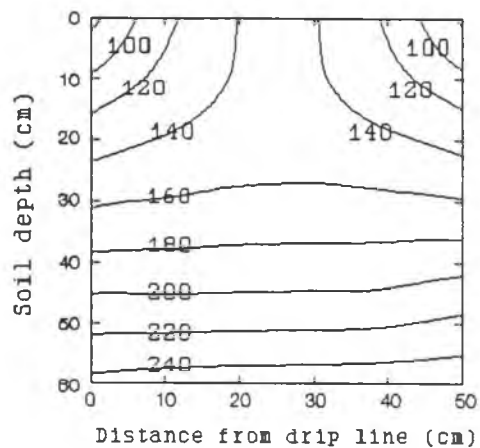
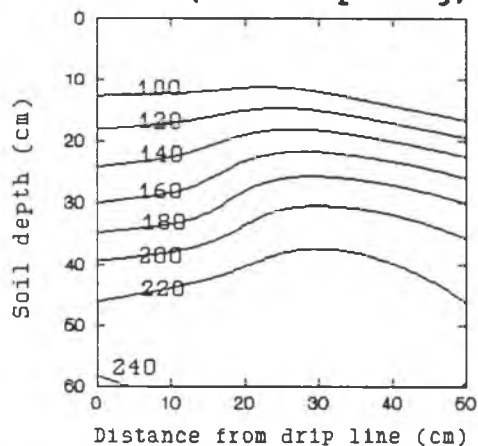


Figure 38 Comparison of soil water potential distributions of treatment C (150 cm spacing) obtained from field experiment and model application for the second and third growth periods of sweet corn.

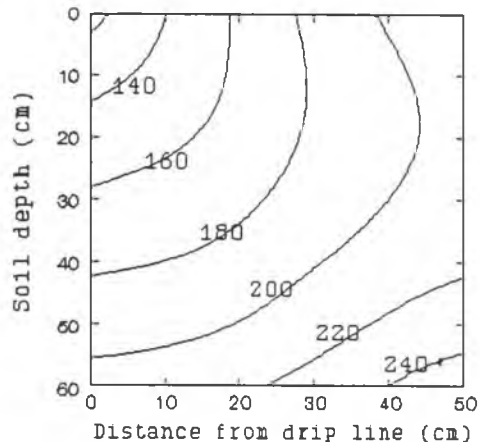
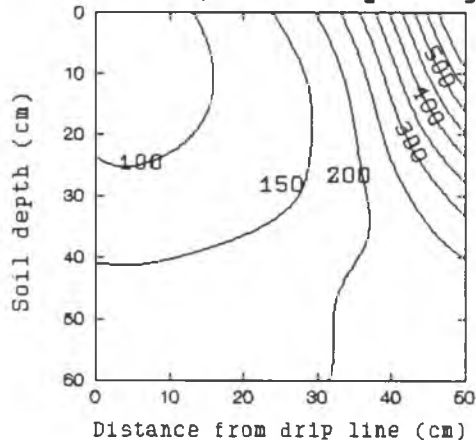
Experimental results

Model results

Treatment A (50 cm spacing):



Treatment B (100 cm spacing):



Treatment C (150 cm spacing):

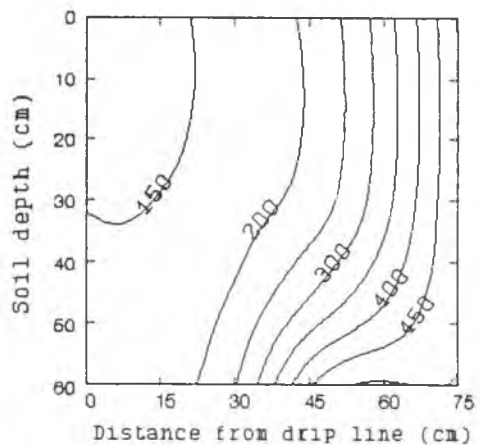
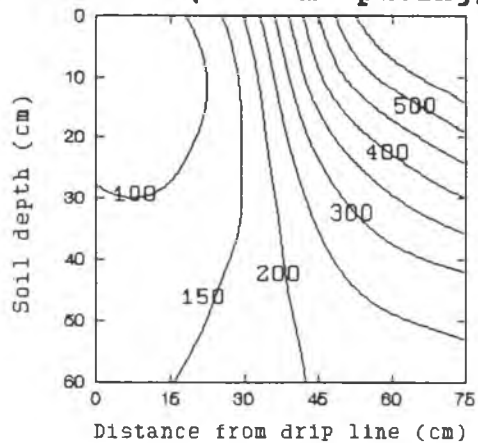


Figure 39 Comparing distribution patterns of the seasonal averaged soil water potential obtained from the field experiment and model application for treatments A, B and C.

The results indicate that the model tends to predict smaller ranges of SWP variation as compared to greater variation in SWP measured under field conditions, particularly for the wider spacings (treatments B and C). The maximum SWP ranges of -100 to -300 cm, -100 to -700 cm and -100 to -800 cm were observed in the field during the third period of growth for treatments A, B and C, respectively, while the ranges of -140 to -220 cm, -120 to -260 cm and -150 to -450 cm were obtained from the model (Figures 36 to 38). However, the model may give symbolic default values of -500 cm at some locations (not shown in Figures) to indicate that model calculations have yielded negative values of the final metric flux potential (ϕ). It is necessary that the metric flux potential found after adding source-sink combinations together be positive (Warrick et.al. 1981).

As previously discussed, the one-dimensional and fractional uptake yielded similar patterns of SWP distributions. The simulation with strip uptake gave different wetting patterns from those of the field experiment. The strip sink also yielded lower SWP values (more negative) compared with the other two root uptake patterns, as indicated by the symbolic default value of -500 cm, as shown in Figures 29, 32 and 35 in section 4.3.

It seems that the linearized model gave good predictions when spacing between line sources was not too

far apart to allow the dry regions to develop between the lines, treatment A for example. For some cases, wider spacings of line sources (treatment C for example) where dry regions usually occurred, the quantitative values of SWP could not be predicted particularly at the midway between lines because of the effect of sink terms. This may also be due to the limiting value of the metric flux potential used in the model calculation, which is taken as zero at large distances from the source or sink (Warrick et.al.,1981).

However, the general patterns of SWP distributions obtained from the field experiment and the model show pattern similarities as shown in Figures 36 to 39. The ranges of SWP values were somewhat different. Some differences in SWP values were probably caused by the model input values of soil hydraulic properties (K_0 and α) and other parameters representing the field conditions, which may deviate from the real situation. In addition, the model was developed with the assumption that the emitter is a continuous wetting source (constant flux at the source), with a uniform porous media. The steady-state condition required for the model rarely occurs under field conditions.

4.5 Evaluation of Model Application

The water flow theory based on Richards' equation is being used in the design of drip irrigation for improving uniformity of water application based on soil hydraulic properties and optimal crop water requirement (Bresler, 1978; Warrick et.al., 1979, 1981; and Amozegar Fard et.al., 1984). These models attempt to integrate the crop, soil and system parameters in the design and operation of drip systems. However, simplification of these models is necessary for practical purposes.

The model described here is that of Warrick et.al. (1979, 1981), namely 'Linearized moisture flow from line source with water extraction' and 'Soil moisture flow for point or line sources --computer programs for linearized solutions'. Parts of the computer program (1981) were modified for two dimensional flow from line sources with or without plant water uptake (Unpublished, Warrick, 1990). This program was written in FORTRAN and is compatible with MS FORTRAN 5.0. as given in Appendix F, and includes subroutines necessary for the available linearized solutions. Linearization was attained in the steady-state case by assuming uniform soil with unsaturated hydraulic conductivity which is exponentially related to soil water pressure head. Not only steady-state but also time-dependent problems can be solved under more restrictive assumptions than those of the steady-state case; a

questionable assumption is that change in hydraulic conductivity with respect to water content is constant, which does not seem to agree with field data of this soil and data reported in the literature.

In addition to the complexities involved in applying mathematical equations for computer simulation, precise field data of soil hydraulic properties or soil parameters are not always easily measured in the field. The model becomes more complicated when water uptake by plants (sink term) is included. The crop parameters such as rooting depth and rate of water uptake obviously vary with plant growth stage, evapotranspiration demand and available water, which of course interact with the water flow not only at the surface but also within the profile by way of differences in plant uptake.

The model outputs (TWO.OUT and TWO.COL) are dependent upon the parameters defined in the data input file (TWO.SPE). The model output quantitatively depends on input parameters. The more precisely parameters are defined, the more reasonable the output from the model. Generally, the crop parameters (rooting depth and root water uptake) result in decreasing (more negative) SWP values, which result from the source-sink combination. The model is also sensitive to soil hydraulic properties (K_0 and α). A higher value of K_0 results in a lower value (more negative) of SWP. An increase of α increases SWP value (less negative); conversely, lower

SWP values (more negative) resulted from the lower values of α . The SWP values appear to be more sensitive to α than to K_0 . An increase in α would not only increase values of SWP in a particular location, but also increase SWP of the entire profile as defined in x and z directions, which indicates relatively uniform flow of water in the soil according to the model prediction. This may also be due to an assumed constant flux from the source.

The comparison between the model and experimental results showed some disagreement in some cases. The reasons for the quantitative discrepancies may be one of the following: (i) lack of accuracy in estimating the parameters (input data) needed such as soil hydraulic properties and root water uptake rate; (ii) inadequacy of the assumptions in developing the model; (iii) deviation of root water uptake approximations in the model from the real situation; (iv) the effect of hysteresis occurring in the field but not in the model calculation. Another effect may result from the fact that the actual field conditions at the soil surface, especially during the initial state of infiltration and redistribution are much more complicated than those assumed in the model. However, the assumption of soil hydraulic conductivity being exponentially related to pressure head was shown previously to be valid for Molokai soil (Santo, 1975). Since the steady state condition was assumed, the model seems to be suitable only for conditions

where variation in soil water conditions is small. According to Warrick (1986), a steady state analysis will be nearly valid for relatively constant environmental conditions, for a plant canopy that is stable and for highly frequent applications of water. However, the field conditions under this study were unlikely to meet the steady-state condition.

Evaluation of root water uptake (sink terms) is difficult to make from this study. The root uptake patterns defined and applied in the model are assumed mathematically to approximate the rate of water uptake by plants, but it is very difficult to predict exactly what patterns of water will be withdrawn from the soil under field conditions. Several root water uptake models (Gardner, 1964; Van Bavel et.al., 1968; Nimah and Hank, 1973; Hillel et.al., 1976; Herkelrath et.al., 1977; Feddes et.al., 1976; Rowse et.al., 1978; Hoogland et.al., 1981; and Molz, 1981) could be used to predict water uptake rate with more accuracy, but more detailed information and data are required for most of these models. To apply such models together with the present water flow model seems to be very complicated and time consuming, thus not suitable for practical purposes, especially for drip irrigation system design. Therefore, it appears that the approximation of one dimensional or fractional water uptake is reasonable for simplicity and practical purposes.

In addition to solving problems for steady state conditions as presented in previous sections, the model is also capable of solving time-dependent problems and time-dependent with cyclic input, that is alternating periods with and without irrigation (wet and dry periods of irrigation cycle). Attempts to apply the model for these cases were made, and it was found that the model gave a reasonable prediction when the sink term was not included. The outputs of a time-dependent case with sink term indicate that the model could only predict pressure heads at locations near line sources and failed to give quantitative results at far distances from the line sources. The model also failed to give predictions for a time-dependent case with sink term and cyclic input, particularly for the time corresponding to the period without water application. Even so, the original programs without modification (Warrick, et.al., 1981) demonstrated that this particular problem could be solved for a point source, but only when a short time length was defined for wet and dry periods. This may be explained by source and sink combinations in which the source continues to be positive for a certain time defined as wet length, while the sink is always negative throughout the time of wet and dry cycle. As a result, the final solution, after adding a source and sink combination together, became negative. This indicates water being withdrawn where no water is available. The model requires

that the final value of metric flux potential must be positive.

Considering the difficulties in estimating the dynamic water conditions in the field, the model results were generally in good agreement with the experimental results, especially for close spacings of line sources. In spite of discrepancies in some cases, the model gave similar patterns of SWP to those of the field results, although their values were somewhat different due to input parameters and assumptions and limitations of the model. An implication is that this model is useful for predicting the wetting patterns which can be used for designing a drip irrigation system design to create desired wetted soil volume in the root zone.

4.6 Evaluation of a Single Value of Soil Water Potential in Relation to Crop Response

Although many studies have shown that crop yield is strongly related to the energy status of water and thus to the soil water potential, its value has also been used as one of the most important parameters determining plant growth and yield (Wierenga and Saddig, 1985). But the soil water potential and water content vary in both space and time, so that the water regime of a soil can not be readily specified as a single water content or a single soil water potential, especially when related to crop response. It is commonly found that soil water potential varies with both time and depth in a single field or plot planted to a given crop in any season (Taylor, 1952). The soil water potential value is a function impacted by three factors, soil, crop, and climate, which change considerably from site to site and from season to season. In addition, the dynamic approach which regards the plant as an integrated part of a soil plant-atmosphere system explains why it is not easy to select a certain constant value of soil water potential which can represent the crop response to soil water conditions.

The results from this study, combined with earlier works on crop response to soil water, point out the difficulty in attempting to use a single value of soil water content or soil water potential to represent the crop water requirement or to describe the water condition in the entire

root zone environment of field crops. This may be a reason why the soil water potential values are usually given as an optimal range for a particular crop. The data obtained from the field experiment demonstrated how yield responds to soil water potential values as presented in sections 4.2.1, 4.2.2, and 4.2.3. A representative value of soil water potential (averaged or integrated value over all depths during the second, third growing periods and the whole growing season) correlated well with the yield of sweet corn (section 4.2.3). The relationship between values of soil water potential at particular depths and crop yield was also considered. The soil water potential at the 15 cm depth yielded a good correlation compared to soil water potential at other depths. This is because soil water potential above 15 cm depth may be considerably affected by evaporation, while changes in soil water potential values at lower depths, i.e. 30 to 60 cm, are much less responsive to evapotranspiration than those at 15 cm (Cary and Fisher, 1983).

Section 4.2.4 presents a single value of soil water potential midway between line sources (h_c) as related to crop yield. Although the use of the h_c value is somewhat arbitrary and questionable, the correlation analysis in this study and other works (Russo, 1983 and 1984) imply that h_c can be used as a soil-crop parameter in drip system design. As previously mentioned, the h_c value and the size of wetted

zones are dependent on both soil (in terms of K_s and α) and irrigation system (in terms of spacing and discharge). Russo (1983, 1984) proposed a method for calculating h_c values based on Bresler's approach (1978), in which the h_c value is a function of K_s , α , spacing (d) and discharge (Q). He concluded from both the theoretical and the experimental results that the calculated steady state h_c and the measured h_c at different times showed a relatively good correlation between the two sets of h_c , although the calculated values of h_c were greater than the measured values of h_c . This is probably due to both measurement error and the limitations of Bresler's (1978) procedure. It should also be noted that the calculated values of h_c were steady state, surface-midway-soil water potentials, whereas the measured h_c were obtained from tensiometers readings (determined midway between emitters, and at the 10-15 cm depth). Also the method of Bresler (1978) used to calculate h_c did not take into account the presence of a root system in the flow domain which acts as a sink in the model calculations. Furthermore, Russo (1984) found that although K_s and α , as well as h_c , varied considerably in the field, the spatial variability of the crop yield was relatively small.

Warrick et al. (1979) developed a simple algebraic formula to calculate soil water potential at the surface, midway between sources (referred as h_m):

$$h_m \approx (1/\alpha) \ln\{(q/K_s L)[\exp(-0.24 \alpha L) + (\exp(-\alpha Z_0) - 1)\gamma_u/(\alpha Z_0)]\}$$

where K_s and α are empirical constants, q is discharge rate, L is spacing between sources, Z_0 is rooting depth and γ_u is relative root uptake, which can be obtained by $\gamma_u = uL/q$ (u is total uptake for a given sink function). The h_m is the soil water potential midway between sources (equivalent to h_c proposed by Bresler, 1978). This formula is valid at least for $\alpha L < 10$. Thus, given the appropriate input parameters, h_m can be easily evaluated on a calculator. Alternately, h_m can be specified and any of the other parameters such as q or L can be found. This approximate formula is, however, valid for steady-state conditions with no surface loss and a uniform uptake function. In order to evaluate this formula (Warrick, et.al., 1979), necessary input parameters used in this study (given in section 4.3) were used in the above equation. Results obtained from this approximate formula were generally much higher (less negative) than measured values of the surface-midway-soil water potential obtained from this field study. For example, the calculated h_m for the third growth period were about -162 to -166 cm, compared with measured values (at the surface midway) of -246 to -825 cm for line spacings of 50 to 150 cm respectively. The calculated h_m , however, decreased within a narrower range as compared with the field data. This may be due to the limitations of assumptions that steady state conditions exist, that there is negligible

surface evaporation, and that the water extraction pattern is uniform and constant. These assumptions are unlikely to exist in the real situation. The field observations and data suggest that evaporation played a very important role, particularly within the surface soil layer. Since surface evaporation was not taken into account for this calculation formula, this may result in significantly higher (less negative) values of calculated h_m . The input parameters such as K_s , α , q and γ_u also affected the calculated h_m values, but only within a narrow range as compared with values observed in the field conditions. Nevertheless, Warrick et al. (1979) view the formulae given as contributing towards the quantification of design and operation of irrigation from line sources. They also know that such results must be tempered by the judgement of the experienced engineer or scientist for each individual case.

The use of a single value of soil water content or soil water potential to relate to crop yield is obviously questionable. The results from this field experiment, however, suggest that a single value, whether the midway soil water potential or the seasonal integrated (averaged) value can be a useful indicator of crop water requirement for use in drip irrigation design. The soil water potential value at the 15 cm depth is recommended, since its variation appears to be more sensitive to crop yield as compared with values at other depths. The use of a single value as the

midway soil water potential (at the 15 cm depth) or the integrated value over depth throughout the growing season is considered to be reasonable for many applications.

According to Gardner and Niemah (1964) such a limiting soil water potential should, however, be seen as a dynamic value, since water conditions in the root zone vary in both space and time.

Therefore, the use of the concept of the midway soil water potential between sources (h_c or h_m) in drip irrigation design as related to crop response is considered a reasonable approach for this purpose, despite the great complexity of such systems in nature. Russo (1983, 1984) also noted that the use of h_c in drip irrigation design is not unlike approaches taken in other types of engineering design.

5. SUMMARY AND CONCLUSIONS

Soil Water Potential and Crop Yield under Drip Irrigation. The results from the field experiment conclusively show the impact of line source spacings on soil water potential distribution patterns and variations, which in turn affect crop growth and yield. For sweet corn growing on the structural silty clay soil, the closer spacing of line sources (one line source for each crop row, treatment A) provided a better uniformity of water application compared to the wider spacing treatments (B and C). The crop response was based on marketable ear yield, mean diameter and length of selected ears, total fresh weight, total dry matter production, leaf area index and plant height. Relationships between soil water potential at different depths, distances from a line source and crop yield were also evaluated from these data. The soil water potential values decreased as distances from a line source increased. Zones of dry soil normally appeared midway between line sources, especially at the soil surface. This is probably due to limited horizontal water movement from a line source for a given amount of water applied, evaporation and water extraction by plants. The distance of plant rows from a line source significantly affected crop yield. The crop yield declined with increasing distance from the line source.

The correlation analysis indicated that both the representative value and midway soil water potential at the 15-cm depth provided good correlations with crop growth and yield. It has been shown in field trials that measurement of soil water potential at the 15 cm depth works well from a practical standpoint (Cary, 1981, Cary and Fisher, 1983).

The representative values over depth and time also correlated well with crop growth and yield. The coefficient of correlation (r) for the second and third growth periods were higher than that obtained for the fourth growth period. However, average soil water potential over depths throughout the growing season also showed a good relationship with crop yield at maturity.

Use of Model for Drip Irrigation System. Recent work on drip irrigation design and management has suggested that drip irrigation may provide better results in crop yield per unit of water applied when the system is adequately installed and operated. Up to the present time, the development in terms of system design appears to be empirical, and few recommendations have been made from research studies on the design for various climate, crop and soil conditions. This may be due to the great complexity of such a system in nature.

Nevertheless, in the past decade many attempts have been made to improve drip irrigation system design for a set

of soil, crop and climatic conditions (Bresler, 1978; Warrick et al., 1981; Amoozegar-Fard et al., 1984; and Schwartzman and Zur, 1987). Soil water flow models for two- or three-dimensional flow from a point or a line source with or without plant uptake have been developed to predict the soil water distribution as an aid to engineering system design. To demonstrate the theoretical estimate of soil water movement horizontally and vertically under drip irrigation (line source) the Warrick et al. (1981) linearized moisture flow model was used to calculate soil water potential for the steady-state and periodic applications. In this study, quantitative soil water potential distribution patterns with different treatments of line spacings are presented, both for the experimental and theoretical cases. The model tends to predict narrower ranges of soil water potential variations as compared to wider variations in soil water potential occurring in the field. However, the model tends to give a good prediction when line spacings are close enough (treatment A for example), so that zones of extremely dry soil do not develop. Furthermore, the model appears to be suitable only for conditions where the variation in soil water potential is relatively small.

Despite the discrepancies between the experimental and the model results, especially for treatments (B and C) with wider spacings of line sources, the agreement is sufficient

for practical application of the theory. Similar patterns of soil water potential distributions were obtained from the model and the experimental results, although their actual values were somewhat different due to input parameters, assumptions and limitations of the model (sections 4.3 and 4.4). The model is useful for prediction purposes and is considered as a step toward a new approach in drip irrigation design. Designers can also make use of this approach to calculate the wetted area and spacing between sources in combination with discharge rate for a particular soil and crop.

Use of a Single Value of Soil Water Potential as Related to Crop Response in Drip Irrigation System Design. The results from this study combined with other works on soil water potential and crop response pointed out the difficulty in attempting to use a single value of soil water potential to describe crop response to the water regime in the root zone. This is because the water content or soil water potential is so variable in both space and time that the water regime of a soil cannot be readily specified as a single value. However, the correlation analysis indicated the midway soil water potential between line source (h_c) at 15-cm depth correlated well with crop yields (section 4.2.4), whereas no correlation was found between the h_c values below 45 cm depth and the yield. A single value of soil water potential

obtained by integration or averaging also correlated well with yield. Thus the use of a single value as the midway soil water potential in drip irrigation system design seems appropriate, as indicated by the good correlation with crop yield. Such a measured value is, however, recommended at the 15-cm depth, because of evaporation impact at the soil surface and the limited variation in soil water potential at greater depths. Alternatively, the representative (integrated/averaged) value of soil water potential may be used to represent crop response or crop water requirement. In any case, such a single value should be viewed as a dynamic value rather than a constant value of soil water potential for a given crop.

APPENDIX A

Mean, standard deviation (SD) and coefficient of variation (CV) for soil water potential data of each treatment.

Example for treatment A: Soil water potential measured at 15-cm depth at position 1 from three replications.

Time (Julian day)	Mean (-cm)	S.D (-cm)	C.V. (%)
165	100.4	7.9	7.9
166	137.9	10.3	7.5
168	112.2	4.1	3.6
170	187.9	12.4	6.6
171	104.1	9.5	9.1
173	172.3	17.4	10.1
174	103.2	8.8	8.5
176	226.3	32.9	14.6
177	79.9	6.7	8.4
179	173.3	15.3	8.8
180	105.7	4.1	3.8
182	275.3	42.9	15.6
183	125.2	10.5	8.4
185	243.4	32.1	13.2
186	125.2	14.7	11.8
188	358.7	54.2	15.1
189	115.0	10.2	8.9
191	404.3	12.8	3.2
192	91.4	4.4	4.8
194	268.8	36.8	13.7
195	106.9	8.4	7.8
197	270.3	37.3	13.8
198	85.8	3.5	4.1
200	216.4	19.7	9.1
201	86.4	7.1	8.2
203	60.1	0.0	0.0
204	79.3	10.7	13.5
206	188.2	14.0	7.4
207	265.1	13.0	4.9
209	428.6	33.3	4.0
210	128.0	13.5	10.6
212	412.7	29.9	7.2
213	142.9	18.7	13.1
215	347.3	52.0	15.0
216	465.4	11.7	2.5

Example for treatment B: depth = 15 cm, position 1

Time (Julian day)	Mean (-cm)	S.D (-cm)	C.V. (%)
165	106.3	11.6	10.9
166	126.8	4.2	3.3
168	110.6	6.5	5.9
170	185.4	9.9	5.4
171	80.8	7.9	9.8
173	152.5	15.1	9.9
174	88.0	10.9	12.5
176	203.4	20.2	9.9
177	70.6	7.4	10.6
179	174.8	15.4	8.8
180	76.2	7.2	9.5
182	236.5	28.1	11.9
183	89.2	7.8	8.7
185	164.9	18.0	10.9
186	89.2	12.0	13.4
188	332.1	39.0	11.8
189	91.4	4.4	4.8
191	283.4	29.1	10.3
192	71.9	12.1	16.9
194	238.1	2.8	1.2
195	82.1	7.1	8.7
197	230.1	6.6	2.9
198	70.3	7.6	10.8
200	200.6	10.3	5.2
201	79.9	9.8	12.3
203	56.3	0.0	0.0
204	78.7	9.8	12.5
206	181.6	23.0	12.7
207	301.1	3.3	1.1
209	827.4	20.6	2.5
210	90.5	15.3	17.0
212	331.8	17.7	5.4
213	75.6	6.6	8.7
215	161.8	27.7	17.1
216	261.4	46.1	17.6

Example for treatment C: depth = 15 cm, position 1

Time (Julian day)	Mean (-cm)	S.D (-cm)	C.V. (%)
165	96.1	11.1	11.6
166	130.2	10.6	8.1
168	99.5	9.7	9.7
170	194.4	18.0	9.3
171	56.1	3.3	5.8
173	124.3	11.8	9.6
174	76.2	3.7	4.9
176	194.7	20.1	10.3
177	65.0	2.7	4.1
179	171.4	20.8	12.1
180	78.4	6.2	7.9
182	267.5	52.8	19.7
183	79.9	5.1	6.4
185	157.2	19.6	12.5
186	100.4	18.7	18.6
188	329.9	61.5	18.7
189	80.6	7.2	9.0
191	349.4	33.0	9.5
192	75.9	2.4	3.2
194	214.8	23.7	11.0
195	79.9	8.3	10.4
197	223.8	40.1	17.9
198	70.9	5.1	7.2
200	178.5	27.4	15.4
201	70.3	7.4	10.5
203	65.7	0.0	0.0
204	82.1	7.4	9.1
206	175.8	29.6	16.8
207	284.6	53.9	18.9
209	740.8	130.4	17.6
210	79.3	4.7	5.9
212	299.8	65.9	15.3
213	77.8	8.1	10.4
215	257.0	5.1	2.0
216	384.5	35.9	9.3

APPENDIX B

**Statistical analysis of yield parameters as affected by
spacings of line sources (wet rows and dry row)**

SAS statements:

```

option ls=72 ps=60;
data raw;
  infile 'a:fwdw.prn';
  input rep sp wd plfw earfw totfw pldw eardw totdw lai;
  if sp = 50 then addl = 0.0;
  if sp = 100 and wd = 1 then addl = 0.0;
  if sp = 100 and wd = 2 then addl = 0.5;
  if sp = 150 and wd = 1 then addl = 0.0;
  if sp = 150 and wd = 2 then addl = 0.75;
  addl2 = addl * addl;
proc print;
proc glm data= raw;
class rep sp wd ;
model plfw earfw totfw pldw eardw totdw lai = rep sp rep*sp
addl addl2 ;
means sp /duncan waller;

```

SAS output:

Spacing (cm)	Wet Dry	Plant fresh wt	Ear fresh wt	Total fresh wt	Plant fresh wt	
REP	SP	WD	PLFW	EARFW	TOTFW	PLDW
1	50	1	4598.61	2640.13	7238.74	858.02
2	50	1	4412.37	3193.11	7605.47	844.63
3	50	1	3947.48	2782.57	6730.04	770.28
1	100	1	3925.17	2594.74	6519.91	733.03
2	100	1	4314.86	3142.29	7457.14	830.53
3	100	1	3491.61	2635.04	6126.65	709.79
1	100	2	3292.04	2255.48	5547.52	607.86
2	100	2	3202.88	2370.00	5572.88	598.99
3	100	2	2928.15	1896.30	4824.45	564.06
1	150	1	4587.43	3129.00	7716.43	865.81
2	150	1	4166.10	3018.60	7184.70	749.47
3	150	1	4816.71	3021.00	7837.71	895.56
1	150	2	3117.00	1906.13	5023.13	569.41
2	150	2	3750.75	2397.60	6148.35	689.22
3	150	2	3014.22	1997.22	5011.43	556.13

REP	SP (cm)	WD	Ear fresh wt ----- (g/m ²) -----	Total fresh wt -----	Leaf area index	Average Distance from drip line (cm)	
			EARDW	TOTDW	LAI	ADDL	ADDL2
1	50	1	580.30	1438.32	4.26	0.00	0.00
2	50	1	696.42	1541.05	4.16	0.00	0.00
3	50	1	577.10	1347.38	4.25	0.00	0.00
1	100	1	579.92	1312.95	4.06	0.00	0.00
2	100	1	655.80	1486.33	4.12	0.00	0.00
3	100	1	569.70	1279.49	4.22	0.00	0.00
1	100	2	479.74	1087.60	3.52	0.50	0.25
2	100	2	527.56	1126.55	3.44	0.50	0.25
3	100	2	406.19	970.25	3.35	0.50	0.25
1	150	1	687.13	1552.94	4.20	0.00	0.00
2	150	1	601.00	1350.47	4.12	0.00	0.00
3	150	1	668.55	1564.11	4.27	0.00	0.00
1	150	2	377.79	947.21	3.56	0.75	0.56
2	150	2	492.95	1182.17	3.65	0.75	0.56
3	150	2	386.86	942.99	3.52	0.75	0.56

General Linear Models Procedure
Class Level Information

Class	Levels	Values
REP	3	1 2 3
SP	3	50 100 150
WD	2	1 2

Number of observations in data set = 15
Dependent Variable: PLFW (Plant fresh weight)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	10	5024131.6	502413.2	3.27	0.1321
Error	4	613773.4	153443.4		
Corrected Total	14	5637905.0			

R-Square	C.V.	Root MSE	PLFW Mean
0.891134	10.20714	391.72	3837.692

Source	DF	Type I SS	Mean Square	F Value	Pr > F
REP	2	304876.2	152438.1	0.99	0.4464
SP	2	1310348.4	655174.2	4.27	0.1018
REP*SP	4	253435.2	63358.8	0.41	0.7937
ADDL	1	3152866.1	3152866.1	20.55	0.0106
ADDL2	1	2605.7	2605.7	0.02	0.9026

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	2	349205.53	174602.76	1.14	0.4062
SP	2	584423.56	292211.78	1.90	0.2624
REP*SP	4	253435.15	63358.79	0.41	0.7937
ADDL	1	62352.54	62352.54	0.41	0.5585
ADDL	1	2605.74	2605.74	0.02	0.9026

General Linear Models Procedure
Dependent Variable: EARFW (Ear fresh weight)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	10	2714830.7	271483.1	7.14	0.0366
Error	4	152056.8	38014.2		
Corrected Total	14	2866887.5			

R-Square	C.V.	Root MSE	EARFW Mean
0.946961	7.502935	194.97	2598.614

Source	DF	Type I SS	Mean Square	F Value	Pr > F
REP	2	385812.4	192906.2	5.07	0.0799
SP	2	307764.0	153882.0	4.05	0.1094
REP*SP	4	80089.4	20022.3	0.53	0.7251
ADDL	1	1940728.9	1940728.9	51.05	0.0020
ADDL2	1	436.1	436.1	0.01	0.9199

General Linear Models Procedure
Dependent Variable: TOTFW (Total fresh weight)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	10	14440947	1444095	4.78	0.0725
Error	4	1207682	301920		
Corrected Total	14	15648629			

R-Square	C.V.	Root MSE	TOTFW Mean
0.922825	8.537089	549.47	6436.303

Source	DF	Type I SS	Mean Square	F Value	Pr > F
REP	2	1187695	593847	1.97	0.2542
SP	2	2826175	1413088	4.68	0.0896
REP*SP	4	381035	95259	0.32	0.8550
ADDL	1	10040867	10040867	33.26	0.0045
ADDL2	1	5175	5175	0.02	0.9022

General Linear Models Procedure
Dependent Variable: PLDW (Plant dry weight)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	10	178666.89	17866.69	2.77	0.1689
Error	4	25776.75	6444.19		
Corrected Total	14	204443.64			

R-Square	C.V.	Root MSE	PLDW Mean
0.873918	11.10540	80.276	722.8527

Source	DF	Type I SS	Mean Square	F Value	Pr > F
REP	2	4828.17	2414.09	0.37	0.7094
SP	2	45196.98	22598.49	3.51	0.1319
REP*SP	4	5812.85	1453.21	0.23	0.9109
ADDL	1	122658.86	122658.86	19.03	0.0120
ADDL2	1	170.02	170.02	0.03	0.8788

General Linear Models Procedure
Dependent Variable: EARDW (Ear dry weight)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	10	143671.15	14367.11	4.45	0.0816
Error	4	12912.51	3228.13		
Corrected Total	14	156583.66			

R-Square	C.V.	Root MSE	EARDW Mean
0.917536	10.28416	56.817	552.4673

Source	DF	Type I SS	Mean Square	F Value	Pr > F
REP	2	14336.98	7168.49	2.22	0.2245
SP	2	16076.80	8038.40	2.49	0.1984
REP*SP	4	6203.71	1550.93	0.48	0.7524
ADDL	1	106419.71	106419.71	32.97	0.0046
ADDL2	1	633.95	633.95	0.20	0.6806

General Linear Models Procedure
Dependent Variable: TOTDW (Total dry weight)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	10	620952.92	62095.29	3.51	0.1187
Error	4	70715.18	17678.79		
Corrected Total	14	691668.09			

R-Square	C.V.	Root MSE	TOTDW Mean
0.897761	10.42574	132.96	1275.321

Source	DF	Type I SS	Mean Square	F Value	Pr > F
REP	2	34336.90	17168.45	0.97	0.4531
SP	2	110876.42	55438.21	3.14	0.1516
REP*SP	4	18016.05	4504.01	0.25	0.8931
ADDL	1	457576.23	457576.23	25.88	0.0070
ADDL2	1	147.30	147.30	0.01	0.9317

General Linear Models Procedure
Dependent Variable: LAI (Leaf area index)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	10	1.7024000	0.1702400	14.39	0.0102
Error	4	0.0473333	0.0118333		
Corrected Total	14	1.7497333			
R-Square		C.V.	Root MSE	LAI Mean	
0.972948		2.779756	0.1088	3.913333	
Source	DF	Type I SS	Mean Square	F Value	Pr > F
REP	2	0.0017733	0.0008867	0.07	0.9291
SP	2	0.3913833	0.1956917	16.54	0.0116
REP*SP	4	0.0046267	0.0011567	0.10	0.9776
ADDL	1	1.2212513	1.2212513	103.20	0.0005
ADDL2	1	0.0833654	0.0833654	7.04	0.0567

Comparison of means for treatments A, BW (B wet row), BD (B dry row), CW (C wet row) and CD (C dry row)

General Linear Models Procedure

Duncan's Multiple Range Test for variable: PLFW

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 8 MSE= 108397.9

Number of Means	2	3	4	5
Critical Range	619.1	645.5	661.0	668.7

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	SP
A	4523.4	3	CW
A			
A	4319.4	3	A
A			
B	3910.5	3	BW
B			
B	3294.0	3	CD
C			
C	3141.0	3	BD

Duncan's Multiple Range Test for variable: EARFW

Alpha= 0.05 df= 8 MSE= 29013.86
 Number of Means 2 3 4 5
 Critical Range 320.3 334.0 342.0 346.0

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	SP
A	3056.2	3	CW
A			
A	2871.9	3	A
A			
A	2790.6	3	BW
B			
B	2173.9	3	BD
B			
B	2100.3	3	CD

Duncan's Multiple Range Test for variable: TOTFW

Alpha= 0.05 df= 8 MSE= 198586.6
 Number of Means 2 3 4 5
 Critical Range 838.0 873.7 894.7 905.1

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	SP
A	7579.6	3	CW
A			
B	7191.4	3	A
B			
B	6701.2	3	BW
C			
C	5394.3	3	CD
C			
C	5314.9	3	BD

Duncan's Multiple Range Test for variable: PLDW

Alpha= 0.05 df= 8 MSE= 3948.7
 Number of Means 2 3 4 5
 Critical Range 118.2 123.2 126.2 127.6

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	SP
A	836.95	3	CW
A			
A	824.31	3	A
A			
A	757.78	3	BW
B			
B	604.92	3	CD
B			
B	590.30	3	BD

Duncan's Multiple Range Test for variable: EARDW

Alpha= 0.05 df= 8 MSE= 2389.527

Number of Means 2 3 4 5

Critical Range 91.92 95.84 98.14 99.28

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	SP
A	652.23	3	CW
A			
A	617.94	3	A
A			
A	601.81	3	BW
B	471.16	3	BD
B			
B	419.20	3	CD

Duncan's Multiple Range Test for variable: TOTDW

Alpha= 0.05 df= 8 MSE= 11093.07

Number of Means 2 3 4 5

Critical Range 198.1 206.5 211.5 213.9

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	SP
A	1489.13	3	CW
A			
A	1442.20	3	A
A			
A	1359.53	3	BW
B	1061.45	3	BD
B			
B	1024.10	3	CD

Duncan's Multiple Range Test for variable: LAI

Alpha= 0.05 df= 8 MSE= 0.006495

Number of Means 2 3 4 5

Critical Range 0.152 0.158 0.162 0.164

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	SP
A	4.2233	3	A
A			
A	4.1967	3	CW
A			
A	4.1333	3	BW
B	3.5767	3	CD
B			
B	3.4367	3	BD

APPENDIX C

Methods for integrating soil water potential

Example of method II (Taylor, 1952) : Treatment A

In the field, measurements of soil water potential were taken at various depths (15, 30, 45 and 60 cm) and at various times during the growing season (165-216 Julian days). At each time a linear regression of soil water potential, T_i , on depth, X , was calculated. The coefficients a_0 , a_1 of equation $T_i = a_0 + a_1X$ were determined.

<u>Time (Julian day)</u>	<u>a_0</u>	<u>a_1</u>
165	98.67	-0.113
168	114.49	-0.124
170	204.93	-1.378
171	93.67	0.280
173	200.36	-1.237
174	154.22	-0.474
176	239.12	-1.305
.	.	.
.	.	.
.	.	.
213	125.34	-2.817
215	365.00	-1.261
216	487.19	-3.159

(T_i is soil water potential at time i , written as a first order polynomial in X).

It was assumed that the time dependence of soil water potential can be approximated by a linear relationship, then it became necessary to calculate the linear regression of a_0 , a_1 on time. This has been done, given the following relations for treatment A:

$$a_0 = p_0(t) = 4.381 t - 635.04$$

$$a_1 = p_1(t) = -0.029 t + 6.034$$

($p_0(t)$ --- $p_r(t)$ represent polynomial in t)

Combining the above equations to the equation

$$T_{ij} = p_0(t) + p_1(t)x + \dots + p_n(t)x^n$$

(T_{ij} is soil water potential at any given depth and at any given time). After rearranging terms leads to

$$T_{ij} = -635.04 + 6.034 x + (4.381 - 0.029 x)t$$

and the irrigation soil water potential is

$$Tr = \int_{t_0}^{t_1} \int_{x=d_0}^{x=d} T_{ij} dx dt$$

$$Tr = \int_{t=165}^{216} \int_{x=15}^{60} [-635.04 + 6.034x + (4.381 - 0.029x)t] dx dt$$

which gives, upon integration, $Tr = 502960$ for all depths and all times. The mean integrated soil water potential representing the mean single observation is obtained by dividing by the number of time intervals and depths represented. This value is $(216 - 165) * (60 - 15) = 2295$, and the mean integrated soil water potential for treatment A is $502960/2295 = 219$ (-cm of water).

Example of method III (Karamanos, 1980) : Treatment A

The average soil water potential at a given time was calculated from the following equation:

$$\bar{\Psi}_{m,s} = \frac{\sum_{z=1}^n (\Delta\theta/\Delta t) z \psi_{m,s,z}}{\sum_{z=1}^n (\Delta\theta/\Delta t) z}$$

where $\Delta\theta/\Delta t$ = the rate of soil water depletion (cm^3 water cm^{-3} soil day^{-1})

$\psi_{m,s,z}$ = the soil matrix potential (MPa) at depth z for the particular time.

n = the number of soil layers

Soil water depletion was determined for periods between two samplings and the rate of depletion at a particular sampling was taken as the average for two successive time intervals. As an example (treatment A), soil samples for water content determination were taken at four depths (15, 30, 45 and 60 cm) on Julian days 180 and 182. Tensiometer readings were also taken at approximately the same time in the same treatment. Note that Julian days 180 and 182 were after and before irrigation times, respectively.

Soil depth (cm)	Soil water potential (cm ³ cm ⁻³)		Soil water potential (-cm)	
	180	182	180	182
----- Julian day -----				
15	36.71	30.84	108	299
30	33.19	30.62	104	232
45	34.72	32.71	178	204
60	33.68	32.04	170	189

Rate of soil water depletion ($\Delta\theta/\Delta t$) was calculated from soil water content taken at two successive intervals (180 - 182 days); results are given below. Soil water potential data were converted from the weight basis (-cm) to the volume basis (MPa)

Soil depth (cm)	$\Delta\theta / \Delta t$ (cm ³ water cm ⁻³ soil day ⁻¹)	Soil water potential (MPa) Julian day 182
$n_1 = 15 (z_1)$	0.0294	- 0.0293
$n_2 = 30 (z_2)$	0.0128	- 0.0227
$n_3 = 45 (z_3)$	0.0110	- 0.0200
$n_4 = 60 (z_4)$	0.0082	- 0.0185

Substituting these values into the given equation results in the average soil water potential of -0.0244 MPa, which is equivalent to -249 cm of water (1 pascal = 10.198×10^{-3} cm of water). The average soil water potential can be calculated for both after and before irrigation times using the same soil water depletion rate for that particular time interval during the growing season.

APPENDIX D

Representative values of soil water potential calculated by simple averaging for particular growth periods of sweet corn.

Treatments	Replications	Growth periods		
		Second -- Soil water	Third potential	Fourth (-cm) --
A	1	138	275	222
	2	151	268	217
	3	139	234	207
		143*	259*	215*
B(wet row)	1	139	187	176
	2	138	234	187
	3	135	183	173
		137*	201*	179*
B(dry row)	1	159	330	210
	2	162	344	235
	3	161	311	199
		161*	328*	214*
C(wet row)	1	124	187	193
	2	111	175	170
	3	116	197	193
		117*	186*	185*
C(dry row)	1	240	539	287
	2	155	540	242
	3	203	574	263
		199*	411*	264*

* mean of three replications

APPENDIX E

Yield of sweet corn at different growth periods.

Treatment	Yield parameters (g/m ²)		
(Growth periods)	Total fresh wt	Total dry wt	LAI
(First growth period 1-20 days)			
A	262.44	31.59	0.38
B(wet row)	233.46	29.52	0.38
B(dry row)	257.04	38.34	0.41
C(wet row)	278.89	39.33	0.45
C(dry row)	240.85	32.94	0.37
(Second growth period 21-40 days)			
A	3505.5	306.00	2.61
B(wet row)	3397.5	274.50	2.44
B(dry row)	3307.5	279.00	2.56
C(wet row)	3379.5	301.50	2.73
C(dry row)	2299.5	216.00	2.25
(Third growth period 41-65 days)			
A	6808.5	1048.50	4.58
B(wet row)	5458.5	801.00	4.27
B(dry row)	5422.5	805.50	3.97
C(wet row)	6844.5	1075.50	4.53
C(dry row)	4284.0	657.00	3.64
(Fourth growth period 41-75 days)			
A	7191.42	1442.25	4.32
B(wet row)	6701.24	1359.59	4.13
B(dry row)	5314.95	1061.47	3.44
C(wet row)	7579.61	1489.17	4.39
C(dry row)	5394.31	1024.12	3.58

APPENDIX F

Computer program for linearized solutions of the model 'Soil moisture flow from line source' (Warrick et.al.,1981; Warrick,1990).

TWO.FOR

```

C *****
C *          TWO - DIMENSIONAL UNSATURATED FLOW          *
C *          LINEARIZED GOVERNING EQ.                   *
C *          (COMPATIBLE WITH MS FORTRAN 5.0   AWW/FEB,1990) *
C *****

C THIS PROGRAM SOLVES THE LINEARIZED GOVERNING EQUATION
C IN TWO - DIMENSIONAL UNSATURATED SOIL PROBLEMS WITH
C SOURCE AND SINK COMBINATIONS.

C SOURCE CAN BE BURIED AT ARBITRARY DEPTH

C INPUT DATA TO BE IN FILE 'TWO.SPE'
C OUTPUT GOES TO FILE 'TWO.OUT'
C CONSTANTS FOR NUMERICAL INTEGRATION ARE IN 'LAGUERRE.DAT'

C *****
C *          DATA NEEDED          *
C *****

C          1) # OF COORDINATES ----- NX,NZ,NT
C          2) ALPHA VALUE ----- ALPHA (CONSTANT IN LINEAR FORM)
C          3) KO VALUE ----- XKO (CONSTANT IN LINEAR FORM)
C          4) LITTLE K VALUE ----- XLK (DERIVATIVE OF THETA
C                                     W.R.T.PHI)
C          5) STRENGTH OF SOURCE ---- QS
C          6) 1-D UPTAKE RATE ----- U (CM/DAY, USE U=0 FOR NO
C                                     UPTAKE)
C          7) DEPTH OF SINK ----- DS
C          8) UPTAKE FRACTIONS ----- UF(I) (I=1,4)
C          9) DEPTH OF SOURCE ----- D
C          10) SPACING OF LINES ----- SPCLIN
C          11) WET LENGTH IN CYCLE --- WETCYC
C          12) DRY LENGTH IN CYCLE --- DRYCYC
C          13) NUMBER OF LINES ----- NLINES
C          14) DESCRIPTION OF STRIPS - QSTRIP(I) (STRENGTH)
C                                     XSTRIP(I) (SEMI-WIDTH)
C                                     ZSTRIP(I) (DEPTH)
C                                     SPCSTRIP(I) (SPACING)
C                                     NLSTRIP(I) (% OF LINES OF
C                                     STRIPS)
C *****
C *          CONTOUR GRAPH DATA -          *
C *****

C          1) WIDTH OF PRINTER PAPER ---- WIDTH

```

```

C          2) LEFT HAND X1 VALUE ----- X1MIN
C          3) RIGHT HAND X1 VALUE ----- X1MAX
C          4) LOWER X2 VALUE ----- X2MIN
C          5) UPPER X2 VALUE ----- X2MAX
C          6) CONTOUR LEVEL UPPER BOUND - CONMAX
C          7) CONTOUR LEVEL LOWER BOUND - CONMIN

C *****
C *                               NON-EXECUTABLES                               *
C *****
COMMON /DATA/   ALPHA,XKO,XLK,QS,ASQ,DSQ,D
COMMON /PARRAY/BIGPHI,TNEW,NL,TOLNL,NLTOT,SPC
COMMON /FUNCT/XEFF,ZEFF,DEFF,XSTRIPEFF,ZSTRIPEFF,NSINGULAR

COMMON /MAP/   AMAP(60,100),DIST(300),DATA(300,3)
COMMON /GRIDD/ WIDTH,X1MIN,X1MAX,X2MIN,X2MAX,CONMAX,CONMIN
COMMON /INTEGRAL/NLAGUERRE,XI(68),WI(68)
DIMENSION HA(20),NSING(20,20),PHIS(20),PSMALL(20,20)
DIMENSION TA(20),XA(20),ZA(20)
DIMENSION UF(4),NLSTRIP(5),QSTRIP(5),SPCSTRIP(5),XSTRIP(5)
DIMENSION ZSTRIP(5),PSTRIP(20,20),PHIDRAIN(20)
DIMENSION AI(68),EX(68),EA(68)
EXTERNAL SLINE,SSTRIP
DATA HEADLIM,TOLNL/-500.0,0.01/
C *****
C * READ/SETUP LAGUERRE COEFFICIENTS (FROM 'LAGUERRE.DAT') *
C *****
OPEN (UNIT=5,FILE='LAGUERRE.DAT')
READ(5,*) NLAGUERRE
DO 100 I=1,NLAGUERRE
READ(5,*) EX(I),XI(I),EA(I),AI(I)
C WRITE(*,*) ' ',I,EX(I),XI(I),EA(I),AI(I)
XI(I)=XI(I)*10.0**EX(I)
AI(I)=AI(I)*10.0**EA(I)
WI(I)=AI(I)*EXP(XI(I))
100 CONTINUE
PRINT *, ' HAVE READ IN LAGUERRE COEFF. NLAGUERRE=',NLAGUERRE
CLOSE(UNIT=5)

C *****
C *                               OPEN OUTPUT FILES                               *
C *          (TWO.OUT = GENERAL, TWO.COL=T,X,Z,H)                               *
C *****
OPEN (UNIT=7,FILE='TWO.COL',STATUS='UNKNOWN')
WRITE(7,*) 'COLUMNS ARE REAL T,X,Z,H'
OPEN (UNIT=6,FILE='TWO.OUT',STATUS='UNKNOWN')
WRITE(6,18)
WRITE(6,*) 'TWO-DIMENSIONAL UNSATURATED FLOW          AWW'
CALL GETDAT(IYR,IMON,IDAY)
CALL GETTIM(IHR,IMIN,ISEC,I100TH)
WRITE(6,34) IHR,IDAY,IMON,IYR
WRITE(6,18)

```

```

C *****
C *           INPUT DATA (TWO.SPE)           *
C *****

OPEN(UNIT=5,FILE='TWO.SPE')
WRITE(6,*)'NLAGUERRE ',NLAGUERRE
READ(5,*)NX,NZ,NT
WRITE(6,*)'NX NZ NT ',NX,NZ,NT
READ(5,*) (XA(I),I=1,NX)
WRITE(6,*) ' X VALUES ',(XA(I),I=1,NX)
READ(5,*) (ZA(I),I=1,NZ)
WRITE(6,*) ' Z VALUES ',(ZA(I),I=1,NZ)
READ(5,*) (TA(I),I=1,NT)
WRITE(6,*) ' T VALUES ',(TA(I),I=1,NT)
READ(5,*)ALPHA,XKO,XLK
WRITE(6,*)'ALPHA XKO XLK ',ALPHA,XKO,XLK
READ(5,*)QS,D,SPCLIN,NLINES
WRITE(6,*)'QS,D,SPCLIN,NLINES ',QS,D,SPCLIN,NLINES
READ(5,*)U,DS,(UF(I),I=1,4)
WRITE(6,*)' U DS UF(1),(2),(3),(4)',U,DS,(UF(I),I=1,4)
READ(5,*) WETCYC,DRYCYC,HEADINI
WRITE(6,*)'WETCYC,DRYCYC,HEADINI ',WETCYC,DRYCYC,HEADINI
I=1
WRITE(6,*) 'VALUES OF I,QSTRIP(I),XSTRIP(I),ZSTRIP(I), SPCSTRIP(I)
1,NLSTRIP(I) FOLLOW:'
110 READ(5,*) QSTRIP(I),XSTRIP(I),ZSTRIP(I),SPCSTRIP(I),NLSTRIP(I)
IF (ABS(QSTRIP(I)) .GT. 1.0E6) THEN
  NSTRIPS=I-1
  WRITE(6,*)' NUMBER OF STRIP SINKS USED -->',NSTRIPS
ELSE
  WRITE(6,*) I,QSTRIP(I),XSTRIP(I),ZSTRIP(I),SPCSTRIP(I),
1 NLSTRIP(I)
  I=I+1
  GOTO 110
END IF
READ(5,*)CONTOUR,WIDTH,X1MIN,X1MAX,X2MIN,X2MAX,CONMAX,CONMIN
WRITE(6,*)'CONTOUR,WIDTH,X1MIN,X1MAX,X2MIN, X1MAX, CONMAX,CONMIN
1',CONTOUR,WIDTH,X1MIN,X1MAX,X2MIN,X2MAX,CONMAX,CONMIN
PRINT *,'DONE WITH INPUT.'
CLOSE(UNIT=5)

C INITIALIZE TO MAKE SURE OF SOME ZEROES
DO IZ=1,NZ
  PHIS(IZ)=0.0
  DO IX=1,NX
    PSTRIP(IX,IZ)=0.0
  END DO
END DO
IF (ABS(HEADINI) .LT. 1.0E6) THEN
  PRINT *,'WILL CALCULATE COMPONENT DUE TO INITIAL CONDITIO'
1 , 'N IF NON-STEADY PROBLEM'
END IF

```

```

C*****
C PART 1 - CALCULATE PHI CONTRIBUTION OF STEP SINK SOLUTION *
C FOR REFERENCE SEE - LINEARIZED MOISTURE FLOW FROM LINE SOURCES *
C WITH WATER EXTRACTION *
C WARRICK, AMOOZEGAR-FARD,LOMEN 1978 *
C*****

```

```

IF (U .LE. 0) THEN
  PRINT *, 'NO 1-D SINK INCLUDED'
ELSE
  ATOT=0
  DO I=1,4
    ATOT=ATOT+UF(I)
  END DO
  IF (ATOT .NE. 1.0) THEN
    PRINT *, 'WARNING SUM OF UF(I) SHOULD BE 1,BUT IS',SS
    PAUSE 'HIT RETURN TO CONTINUE'
  END IF
  A4=4.0*UF(4)/DS
  SS=0
  DO I=1,3
    SS=SS+UF(5-I)
    UF(4-I)=UF(4-I)-SS
  END DO
  DO IZ=1,NZ
    ASQ=A4
    DO I=1,4
      ASQ=UF(5-I)/UF(4)*A4
      DSQ=(5-I)*DS/4.0
      PHIS(IZ)=PHIS(IZ)+PHISS(ZA(IZ))
    END DO
    PHIS(IZ)=U*PHIS(IZ)
  END DO
END IF

```

```

C*****
C PART 2, CALCULATE PHI OF STEADY-STATE STRIPS. NORMALLY CONSIDER *
C AS SINKS, BUT CAN ALSO BE SOURCES. *
C (REFERENCE SSSA J. 1983, P. 870) *
C*****

```

```

IF (NSTRIPS .LE. 0) THEN
  PRINT *, 'NO STRIP SINKS CONSIDERED'
ELSE
  DO IB=1,NSTRIPS
    NLTOT=0
    NL=NLSTRIP(IB)
    XSTRIPEFF=ALPHA*XSTRIP(IB)/2
    ZSTRIPEFF=ALPHA*ZSTRIP(IB)/2
    SPC=SPCSTRIP(IB)
  END DO

```

```

DO IZ=1,NZ
  DO IX=1,NX
    CALL PHIARRAY(ALPHA*XA(IX)/2,ALPHA*ZA(IZ)/2,SSTRIP)
    PSTRIP(IX,IZ)=PSTRIP(IX,IZ)+QSTRIP(IB)/2.0/3.141593*BIGPHI
  END DO
END DO
PRINT *, '      STRIP, NLTOT-->', IB,NLTOT
END DO
END IF

```

```

C*****
C PART 3, CALCULATE PHI OF LINE SOURCE ARRAY AND ADD TOGETHER FOR ANSWER
C           (ALSO INCLUDES 1-D DRAINAGE IF WANT)
C   FOR REFERENCE SEE - LINEARIZED MOISTURE FLOW WITH LOSS AT SOIL
C           SURFACE, LOMEN + WARRICK 1978
C*****

```

```

NLTOT=0
NL=NLINES
SPC=SPCLIN
TCNST=ALPHA*XLK/4.0
IF (TA(1) .LE. 0) THEN
  WRITE(6,*) 'STEADY STATE'
  WETCYC=1000
  BEGICYC=TA(1)+WETCYC
  NT=1
END IF
DO 510 IT=1,NT
DO IZ=1,NZ
  DO IX=1,NX
    PSMALL(IX,IZ)=0.0
  END DO
END DO
IDATA=0
IF (QS .EQ. 0) GOTO 470
WET=1
WRITE (6,18)
WRITE (6,*) 'T =',TA(IT)
WRITE (6,*) 'H VALUES FOLLOW'
WRITE (6,36) (XA(I),I=1,NX)
IF (TA(IT) .GT. 0) BEGICYC=0
TNEW=TCNST*(TA(IT)-BEGICYC)
150 DO 460 IZ=1,NZ
  Z=ZA(IZ)*ALPHA/2.0
  DO 450 IX=1,NX
    X=XA(IX)*ALPHA/2.0
    CALL PHIARRAY(X,Z,SLINE)
    NSING(IX,IZ)=NSINGULAR
    PSMALL(IX,IZ)=PSMALL(IX,IZ)+WET*QS*BIGPHI/2.0/3.14159
450 CONTINUE
460 CONTINUE
WET=-WET

```

```

IF (WET .LT. 0) THEN
  TNEW=TCONST*(TA(IT)-BEGCYC-WETCYC)
ELSE
  BEGCYC=BEGCYC+WETCYC+DRYCYC
  TNEW=TCONST*(TA(IT)-BEGCYC)
END IF
IF (TNEW .GT. 0) GO TO 150
C***** NOW HAVE PSMALL FOR SOURCE ARRAY
470 DO IZ=1,NZ
  PHIDRAIN(IZ)=0.0
  IF ((TA(IT) .GT. 0) .AND. (ABS(HEADINI) .LT. 1.0E6)) THEN
    PHIDRAIN(IZ)=THETAU(ZA(IZ),TA(IT),HEADINI)
  ENDIF
  DO IX=1,NX
    IDATA=IDATA+1
    DATA(IDATA,1)=XA(IX)
    DATA(IDATA,2)=ZA(IZ)
    DATA(IDATA,3)=0
    IF (NSING(IX,IZ) .EQ. 0) THEN
C      NSING(IX,IZ) SHOULD BE 1 WHEN LINE HAD SOME SINGULAR
C      POINTS. ASSIGNED FROM NSINGULAR IN SLINE FUNCTION.
C      IF(XA(IX)**2+(ZA(IZ)-D)**2 .GT. 0.0001) THEN
C        *** ADDING TOGETHER 1-D SINK, 2-D SINK AND SOURCE ***
C        PRINT *, 'T,STRIP,PSMAL ',TA(IT),PSTRIP(IX,IZ),PSMALL(IX,IZ)
C          PSMALL(IX,IZ)=PHIS(IZ)+PSTRIP(IX,IZ)+PSMALL(IX,IZ)
1        +PHIDRAIN(IZ)
      IF (PSMALL(IX,IZ) .GT. 0) THEN
        DATA(IDATA,3) = ALOG(PSMALL(IX,IZ)*ALPHA/XKO)/ALPHA
      ELSE
        DATA(IDATA,3) = HEADLIM
      END IF
    END IF
    HA(IX)=DATA(IDATA,3)
    WRITE(7,40)TA(IT),XA(IX),ZA(IZ),DATA(IDATA,3)
  END DO
  WRITE (6,38) ZA(IZ), (HA(I),I=1,NX)
END DO
PRINT *, '          TIMES USED ALL NL FOR LINES-->',NLTOT
ND=NX*NZ
IF (CONTOUR .EQ. 1) CALL GRID(ND,TA(IT))
IF (CONTOUR .EQ. 0) PRINT *, 'CONTOUR IS OFF'
510 CONTINUE

C  WRAP UP
CALL GETTIM(IHRE,IMINE,ISECE,I100TH)
TT = (IHRE-IHR)*60 + (IMINE-IMIN) + (ISECE-ISEC)/60.
WRITE(6,32)
WRITE(6,18)
WRITE (6,*) ' TIME OF RUN (MIN) -->',TT
CLOSE(UNIT=6)
CLOSE(UNIT=7)
PRINT *,CHAR(7)

```

STOP

```
C*****
  4 FORMAT (' ',31X,'USING STEP SINK')
 18 FORMAT (' ',75('-'))
 32 FORMAT(' ')
 34 FORMAT(' >>>>> HR DAY MONTH YEAR',5I5)
 36 FORMAT(' Z\X',15F6.0)
 38 FORMAT(' ',15F6.0)
 40 FORMAT(8F10.1)
```

C

END

SUBROUTINE PHIARRAY(XX,ZZ,F)

```
C*****
C FINDS BIGPHI FOR ARRAY OF LINES, STRIPS OR RECTANGLES *
C FF IS FUNCTION TO CALCULATE FOR SINGLE SOURCE *
C FORM OF FF IS FF(XXX,ZZZ,TNEW) *
C*****
```

```
COMMON /DATA/ ALPHA,XKO,XLK,QS,ASQ,DSQ,D
COMMON /PARRAY/BIGPHI,TNEW,NL,TOLNL,NLTOT,SPC
COMMON /FUNCT/XEFF,ZEFF,DEFF,XSTRIPEFF,ZSTRIPEFF,NSINGULAR
C PRINT *, 'IN PHIARRAY VALUES OF NL,SPC ARE ',NL,SPC
BIGPHI=0
NSINGULAR=0
XSHIFT=0
DEFF=ALPHA*D/2
BIGL=SPC*ALPHA/2
DO INL=1,NL
  IF (XSHIFT .GT. 0) THEN
    XREL=XX-XSHIFT
    XSHIFT=-XSHIFT
  ELSE
    XREL=XX-XSHIFT
    XSHIFT=-XSHIFT+BIGL
  END IF
  DELTA=F(XREL,ZZ,TNEW)
  IF (NSINGULAR .EQ. 1) THEN
    BIGPHI=0
    RETURN
  ENDIF
  BIGPHI=BIGPHI+DELTA
  IF (INL .LT. NL) THEN
    IF (ABS(DELTA/BIGPHI) .LT. TOLNL) GOTO 100
  ELSE
    NLTOT=NLTOT+1
  END IF
END DO
100 RETURN
END
```

```

FUNCTION SLINE(XXX,ZZZ,TNEW)
C CALCULATES SINGLE LINE DIMENSIONESS PHI. ASSUMES
C TNEW WILL BE NEGATIVE FOR STEADY STATE
COMMON /FUNCT/XEFF,ZEFF,DEFF,XSTRIPEFF,ZSTRIPEFF,NSINGULAR
EXTERNAL AFUN,BFUN,CFUN
IF (XXX**2+(ZZZ-DEFF)**2 .EQ. 0.0) THEN
  NSINGULAR=1
  SLINE=0
  RETURN
END IF
XEFF=XXX
ZEFF=ZZZ
SHIFTINT=0.5
IF (TNEW .LE. 0.0) THEN
C (STEADY-STATE)
  S1=EXP(ZZZ-DEFF)*BKZER(SQRT(XXX**2.0+(ZZZ-DEFF)**2.0))
  S2=EXP(ZZZ-DEFF)*BKZER(SQRT(XXX**2.0+(ZZZ+DEFF)**2.0))
  SS=-2.0*EXP(2.0*ZZZ)*FUN(0.0,CFUN)
  SS=S1+S2+SS
C ELSE
  (NON-STEADY STATE)
  ZEFF=ZZZ-DEFF
  IF (TNEW .LE. SHIFTINT) THEN
    CALL QSIMP(AFUN,0.0,TNEW,S)
    S1=0.5*EXP(ZEFF)*S
  ELSE
    S1=BKZER(SQRT(XXX**2.0+(ZZZ-DEFF)**2.0))
    S1=S1-0.5*FUN(TNEW,AFUN)
    S1=EXP(ZEFF)*S1
  END IF
  ZEFF=ZZZ+DEFF
  IF (DEFF .EQ. 0.0) THEN
    S2=S1
  ELSE
    CALL QSIMP(AFUN,0.0,TNEW,S)
    S2=0.5*EXP(-2*DEFF+ZEFF)*S
  END IF
  IF (TNEW .LE. SHIFTINT) THEN
    CALL QSIMP(BFUN,0.0,TNEW,S)
    S=-1.772454*S
  ELSE
    S=-2.0*FUN(0.0,CFUN)+1.772454*FUN(TNEW,BFUN)
  END IF
  SS= EXP(2.0*ZZZ)*S
  SS=S1+S2+SS
END IF
100 SLINE=SS
RETURN
END

FUNCTION SSTRIP(XXX,ZZZ,TNEW)

```

```

C CALCULATES SINGLE STRIP DIMENSIONLESS PHI.  PRESENTLY SET FOR
C STEADY-STATE ONLY WITH TNEW A DUMMY
COMMON /FUNCT/XEFF,ZEFF,DEFF,XSTRIPEFF,ZSTRIPEFF,NSINGULAR
EXTERNAL STRIP
SSTRIP=TNEW
XEFF=XXX
ZEFF=ZZZ
XX=FUN(0.0,STRIP)
C   SSTRIP=3.141593/4.0/XSTRIPEFF/ZSTRIPEFF*EXP(2*ZZZ)*XX
   SSTRIP=1.772454/4.0/XSTRIPEFF*XX
RETURN
END

FUNCTION STRIP(TAU)
C   INTEGRAND FOR RECTANGULAR SINK/SOURCE
COMMON /FUNCT/XEFF,ZEFF,DEFF,XSTRIPEFF,ZSTRIPEFF,NSINGULAR
RT=SQRT(TAU)
R2=2*RT
X=XEFF
Z=ZEFF
XO=XSTRIPEFF
ZO=ZSTRIPEFF
GX=ERF((X+XO)/R2)-ERF((X-XO)/R2)
C   F1M=EXP(-2*Z-TAU)*(ERF(ZO/R2+RT*(1-Z/R2))-ERF(RT*(1-Z/R2)))
C   F1P=EXP(-TAU)*(ERF(ZO/R2 + RT*(1+Z/R2))-ERF(RT*(1+Z/R2)))
C   F2=4.0*RT*((Z/R2+RT)*ERF(Z/R2+RT)+0.564190*EXP(-(Z/R2+RT)**2))
C   Z=Z+ZO
C   STRIP=4.0*RT*((Z/R2+RT)*ERF(Z/R2+RT)+0.564190*EXP(-(Z/R2+RT)**2))
C   STRIP=F1M+F1P-2*ZO+STRIP-F2
F1=EXP(Z-ZO-TAU-(Z-ZO)**2/4.0/TAU)
F2=EXP(Z-ZO-TAU-(Z+ZO)**2/4.0/TAU)
F3=-R2*1.772454*EXERF(2.0*Z,Z+ZO/R2 + RT)
STRIP=(F1+F2+F3)*GX/RT
RETURN
END

FUNCTION AFUN(TAU)
C   NEEDED FOR BURIED LINE INTEGRAL

COMMON /FUNCT/XEFF,ZEFF,DEFF,XSTRIPEFF,ZSTRIPEFF,NSINGULAR
XMIX=-TAU-(XEFF**2.0+ZEFF**2.0)/(4.0*TAU)
1 AFUN=EXP(XMIX)/TAU
RETURN
END

FUNCTION BFUN(TAU)
C   NEEDED FOR FINITE DEPTH LINE INTEGRAL
COMMON /FUNCT/XEFF,ZEFF,DEFF,XSTRIPEFF,ZSTRIPEFF,NSINGULAR
RT=SQRT(TAU)
BX=-0.25*XEFF**2/TAU
BY = (ZEFF+2.0*TAU)/(2.0*RT)
BFUN = EXERF(BX,BY)/RT

```

```

RETURN
END

FUNCTION CFUN(TAU)
C      NEEDED FOR FINITE DEPTH STEADY STATE LINE
COMMON /FUNCT/XEFF,ZEFF,DEFF,XSTRIPEFF,ZSTRIPEFF,NSINGULAR
TAU=TAU+ZEFF+DEFF
CFUN=EXP(-TAU)*BKZER(SQRT(XEFF**2.0+TAU**2.0))
RETURN
END

FUNCTION THETAU(XX,TT,HH)
C FROM 1975 SOIL SCIENCE, VOL. 120, P. 79
C CALCULATES SMALL PHI FOR DRAINAGE, INTIAL H IS HH.
C ASSUMES XX, TT ARE THE REAL DEPTH(CM) AND TIME(DAYS)
C HH IS THE INITIAL HEAD (HH < 0). IN THE 1975 PAPER
C BIGX=ALPHA*DEPTH AND BIGT=ALPHA*SMALL K* DEPTH.
COMMON /DATA/ ALPHA,XKO,XLK,QS,ASQ,DSQ,D
X=ALPHA*XX
T=ALPHA*XLK*TT
PHILIM=XKO/ALPHA*EXP(ALPHA*HH)
RT=SQRT(TT)
X2=X/2.0/RT
T2=RT/2
F1=-0.5*(X+T+1)*EXERF(X,X2+T2)
F2=0.564190*RT*EXP(-(X2-T2)**2)
F3=0.5*EXERF(0.0,X2-T2)
F1=F1+F2+F3
THETAU=PHILIM*(1.0-F1)
RETURN
END

FUNCTION PHISS(ZZ)
C      ONE-DIMENSIONAL STEP SINK. ZZ,DS HAVE DIMENSIONS
COMMON /DATA/ ALPHA,XKO,XLK,QS,ASQ,DSQ,D
IF (ZZ .LE. DSQ) THEN
  PHISS=-ASQ/ALPHA**2*( (ALPHA*ZZ+1)-EXP(ALPHA*(ZZ-DSQ)))
ELSE
  PHISS=-ASQ*DSQ/ALPHA
ENDIF
RETURN
END

$INCLUDE: 'CONTOUR.FOR'
C      GRID AND PLOT FUNCTIONS

$INCLUDE: 'WMATH.FOR'
C      ERF, QSIMP, MIDPNT, FUN, EXERF, BKZER FUNCTIONS OR SUBROUTINES

```

CONTOUR.FOR

SUBROUTINE GRID(ND,T)

```

C*****
C
C THIS CONTOUR PLOTTER ROUTINE WAS DEVELOPED BY JOHN C. DAVIS
C IN STATISTICS AND DATA ANALYSIS IN GEOLOGY,WILEY,NEW YORK,1973.*
C MINOR MODIFICATIONS WERE MADE TO ADAPT IT TO THESE PROBLEMS
C
C*****

COMMON /MAP/ AMAP(60,100),DIST(300),DATA(300,3)
COMMON /GRIDD/ WIDTH,X1MIN,X1MAX,X2MIN,X2MAX,CONMAX,CONMIN
PRINT *, 'WORKING ON GRID--WILL TAKE A WHILE'
N = ND
ND = 200

C *****
C * CALCULATE MAP SIZE AND SCALE PARAMETERS *
C *****
IW = WIDTH*10.0
IH = WIDTH*6.0*(X2MIN-X2MAX)/(X1MAX-X1MIN)
DX1 = (X1MAX-X1MIN)/FLOAT(IW-1)
DX2 = (X2MAX-X2MIN)/FLOAT(IH-1)
SMALL = (DX1*DX1+DX2*DX2)/10000.0

C *****
C * CALCULATE MAP VALUES *
C *****

105 X2 = X2MAX
DO 100 I=1,IH
X1 = X1MIN
DO 101 J=1,IW

C*****
C CALCULATE DIST**2 BETWEEN CURRENT GRID POINT AND ALL DATA POINTS *
C*****

DO 102 K=1,N
DIST(K) = (X1-DATA(K,1))**2+(X2-DATA(K,2))**2
102 CONTINUE

C *****
C * FIND THE SIX NEAREST DATA POINTS AND CALCULATE SUMS *
C *****
S1 = 0.0
S2 = 0.0
DO 103 K=1,6
IC = 1
DO 104 L=2,N
IF (DIST(L) .LT. DIST(IC)) IC=L

```

```

104 CONTINUE
  IF (DIST(IC) .LT. SMALL) GO TO 10
  D = SQRT(DIST(IC))
  S1 = S1+DATA(IC,3)/D
  S2 = S2+1.0/D
  DIST(IC) = +9.0E+35
103 CONTINUE

C *****
C *          CALCULATE GRID POINT AND STORE IN MATRIX          *
C *****

  AMAP(I,J) = S1/S2
  GO TO 11
10 AMAP(I,J) = DATA(IC,3)
11 X1 = X1+DX1
101 CONTINUE
  X2 = X2-DX2
100 CONTINUE

C *****
C *                                PRINT MAP                                *
C *****
PRINT *, 'NOW CALL PLOT'
CALL PLOT(T, IH, IW, X1MAX, X1MIN, X2MAX, X2MIN, CONMAX, CONMIN)
RETURN
END

SUBROUTINE PLOT(T, NR, MC, X1M, X1S, X2M, X2S, CMAX, CMIN)
COMMON /DATA/  ALPHA, XKO, XLK, QS, ASQ, DSQ, D
COMMON /MAP/   Y(60,100), DIST(300), DATA(300,3)
DIMENSION IOUT(100), ICHAR(9)
C *****
C * DATA CARD HAS CHARACTERS PRINTED OUT ON CONTOURS          *
C *****

DATA ICHAR/" ", "2", " ", "4", " ", "6", " ", "8", " "/
YMAX = CMAX
YMIN = CMIN

C *****
C *                                PRINT MAP ONE LINE AT A TIME          *
C *****

104 WRITE(6,2004) T
  IF(T .EQ. 0.0) WRITE(6,2009)
  WRITE(6,2001)
  WRITE(6,2005) X1S, X1M, X2M
  DO 101 I=1, NR
  DO 102 J=1, MC
  IY = ((Y(I,J)-YMIN)/(YMAX-YMIN))*9.0+1.0
  IF (IY .GT. 9) IY=9
  IF (IY .LT. 1) IY=1

```

```

      IOUT(J) = ICHAR(IY)
102 CONTINUE
      WRITE(6,2002) (IOUT(J),J=1,MC)
101 CONTINUE
      WRITE(6,2006) X2S
      WRITE (6,2001)
      WRITE (6,2007)
      CINT = (YMIN-YMAX)/9.0
      RHS = YMIN
      DO 103 I=1,9
      XLHS = RHS-CINT
      PRHS = EXP(RHS*ALPHA)*XKO/ALPHA
      PLHS = EXP(XLHS*ALPHA)*XKO/ALPHA
      WRITE(6,2003) RHS,XLHS, ICHAR(I),PRHS,PLHS
103 RHS = XLHS
2001 FORMAT(' ')
2002 FORMAT('      I ',100A1)
2003 FORMAT(' ',F10.0,' - 'F5.0,7X, ' -'A1' -      'F5.0' - 'F5.0)
2004 FORMAT(//,10X,'CONTOUR GRAPH OF PRESSURE HEAD VALUES '
1'AT TIME T = ',F10.5)
2005 FORMAT(6X,F4.2,18X,'X-AXIS (SOIL SURFACE)',18X,F6.2,/,6X,70(' -'
1),/,F6.2'I')
2006 FORMAT(1X,F5.1)
2007 FORMAT(15X,'CONTOUR TABLE'/' ',45(' -')//12X'HEAD'25X'PHI',/,
1 ' ',45(' -'))
2008 FORMAT(2F10.5)
2009 FORMAT(30X,'(STEADY STATE)')
      RETURN
      END

```

WMATH.FOR

```

FUNCTION ERF(X)
ERF=1.0-EXERF(0.0,X)
RETURN
END

```

```

SUBROUTINE QSIMP(FUNC,A,B,S)
C MODIFY AS ON P. 117 OF PRESS
EXTERNAL FUNC
COMMON /INTEGRAL/NLAGUERRE,XI(68),WI(68)
PARAMETER ( EPS=0.01,JMAX=10)
OST=-1.E30
OS= -1.E30
DO 11 J=1,JMAX
CALL MIDPNT(FUNC,A,B,ST,J)
S=(9.*ST-OST)/8.
IF (ABS(S-OS).LT.EPS*ABS(OS)) RETURN
OS=S
OST=ST
11 CONTINUE
PRINT *, 'TOO MANY STEPS--S,OS WERE ',S,OS
END

```

```

SUBROUTINE MIDPNT(FUNC,A,B,S,N)
IF (N.EQ.1) THEN
S=(B-A)*FUNC(0.5*(A+B))
IT=1
ELSE
TNM=IT
DEL=(B-A)/(3.*TNM)
DDEL=DEL+DEL
X=A+0.5*DEL
SUM=0.
DO 11 J=1,IT
SUM=SUM+FUNC(X)
X=X+DDEL
SUM=SUM+FUNC(X)
X=X+DEL
11 CONTINUE
S=(S+(B-A)*SUM/TNM)/3.
IT=3*IT
ENDIF
RETURN
END

```

```

FUNCTION FUN(A,FUNC)
C INTEGRAL FROM A TO INFINITY OF FUNC
COMMON /INTEGRAL/NLAGUERRE,XI(68),WI(68)
FUN=0.0
DO 1 I=1,NLAGUERRE
XX=XI(I)

```

```

1     FUN=WI(I)*FUNC(XX+A)+FUN
      CONTINUE
      RETURN
      END

      FUNCTION EXERF(X,Y)
C     EXERF = EXP(X) * ERFC(Y)
C     Y CAN BE NEGATIVE OR POSITIVE
      Y2 = Y*Y
C     EP = EXP(X - Y2)
      IF(Y-4. ) 1,1,2
1     T= 1./ (1. + .3275911 * ABS(Y))
      T2 = T * T
      T4 = T2 * T2
      EXERF=EXP(-Y2)*(.254829592*T - .284496736 * T2 +1.421413741*
1     T*T2 -1.453152027 *T4 + 1.061405429 * T*T4)
      IF(Y)3,3,4
3     EXERF= EXP(X)* ( 2.-EXERF)
      RETURN
4     EXERF= EXP(X)* EXERF
      RETURN
2     Y4= Y2*Y2
      EXERF= 1./Y/ 1.77245385 * (1. - .5/Y2 + .75/Y4-1.875/Y4/Y2
1     +6.5625 /Y4/Y4) *EXP(X- Y2)
      RETURN
      END
      FUNCTION BKZER(X)
      REAL IZ
C MOD. BESSEL, SEC. KIND, ZERO ORDER, A. S. PAGE 378-9.
      IF(X-2)1,1,2
1     T= X/ 3.75
      T2= T*T
      T4= T2*T2
      T8= T4*T4
      IZ=1. + 3.5156229*T2 + 3.0899424* T4 +1.2067492*T2*T4
1     + .2659732*T8 + .0360768*T8*T2 + .0045813*T8*T4
      X2= .5* X
      BKZER= -ALOG(X2)* IZ - .57721566 +.42278420 * X2**2
1     +.23069756* X2**4 +.03488590* X2**6 +.00262698*X2**8
1     +.00010750* X2**10 + .0000074 *X2** 12
3     FORMAT(6E20.6)
      RETURN
2     X2=2./X
      BKZER=EXP(-X)/SQRT(X)* ( 1.25331414 - .07832358*X2
1     +.02189568* X2**2 - .01062446*X2**3 +.00587872*X2**4
1     -.0025154 * X2**5 + .00053208 *X2**6)
      RETURN
      END

```

LAGUERRE.DAT

68

-1. .211068726530635220070323832260 -1. .530370973397610549801512510898
 0 .111223048437012445800224704502 0 .112845824655176078078574120537
 0 .273398752901179114558053494793 0 .150824523158723628358897930327
 0 .507755460397669376483711798401 0 .162791336311942126686867401876
 0 .814421367610832899479577355234 0 .151856410604663669874682374245
 1. .119355999096479203214245400918 0 .125936258232099794354463029788
 1. .164537329739714440128498508065 -1. .941989305849645317932854044647
 1. .217010279385679998723230691768 -1. .640788141334410798623791911659
 1. .276803037643665158180773817276 -1. .39845645824528403068582646289
 1. .343947921984755245461076725347 -1. .227241364420953881461517140200
 1. .418484147744876557445701379924 -1. .119122354893055369147185204210
 1. .500444589556563127113463386666 -2. .574831064380665700668677834710
 1. .589882611848984319108532199296 -2. .255593490701437950942561655930
 1. .686845509250623008878184109940 -2. .104781228211460596729318007367
 1. .791388018477499758323865543384 -3. .396170004817089372461265053362
 1. .903569826821440482480788295971 -3. .138162062901931209084723222935
 2. .102345577080578834289312531437 -4. .444397608439257243945378045117
 2. .115111605640346479275649208384 -4. .131804665685672437551106817961
 2. .128662650273698293415573189332 -5. .360336936646654482712842944054
 2. .143006881144291036883931172922 -6. .907604328516954032332156631219
 2. .158153086418496730822978750985 -6. .210492690623815202669713209195
 2. .174110705114662393112032857615 -7. .449187564805032992153788588886
 2. .190889863373352472421705057992 -8. .881297288802648284367715818934
 2. .208501414517786565045772338057 -8. .158829738991572736262990022395
 2. .22695698332725939031675900089 -9. .262677884829491417229989497338
 2. .246269015008710592335891521567 -10. .398218573048395934725754789267
 2. .266450829424519168135856399213 -11. .552719967002581891049829453946
 2. .287516681220135784453828954023 -12. .701467442223044113857069612792
 2. .309481826595921531140185879035 -13. .812855624829291335492854268199
 2. .332362597586725128020024823033 -14. .858730494786093232525006027517
 2. .356176484854260804282491873301 -15. .825692287568621135842381550643
 2. .380942230166181738831571146644 -16. .721307609095154070014546003294
 2. .406679929938066862302181947480 -17. .571380677753643890612964311082
 2. .433411151458153904635157647809 -18. .409571038310935543494897276716
 2. .461159063709455289801104575831 -19. .265067363662331612690283537244
 2. .489948585062518794757917404656 -20. .154509068764347648625851884081
 2. .519806550550775807202038076124 -22. .809068854452547859092302027718
 2. .550761901980165393328802290839 -23. .379508612902263723773773365613
 2. .582845904792923431718316922859 -24. .158976125029105681154909927478
 2. .616092396438077915661341138800 -26. .592753151415180129560046465149
 2. .650538072045993262094357822049 -27. .196011289378289649271510725105
 2. .686222814525031606032873402253 -29. .572596958723365466556557573245
 2. .723190077881124757944422470889 -30. .14713595468127728255615851295
 2. .761487334723140004093048885066 -32. .331022868943231238134295458272
 2. .801166601720140386861793843113 -34. .648691570158908267730714885517
 2. .842285060446555815245578716780 -35. .110105440974483927565753832719
 2. .884905795906398737750845746120 -37. .160866186116719131659120221854
 2. .929098681523812233828805016733 -39. .200913705664129961284549394692
 2. .974941448186410081025885214049 -41. .212867331508444274251628364474

3. .102252098700678356063481172647 -43. .189686223120091060215456475899
3. .107193495229246481566579218939 -45. .140799436739288246229722967186
3. .112329375502874334972364386670 -48. .861129949523873538993661528496
3. .117672307148599103574011123129 -50. .428597496550211236686087186032
3. .123236704196417779638124745312 -52. .171144932585759488836881989277
3. .129039241036548209525333957251 -55. .539343758123333975447946292246
3. .135099397173572605245413893723 -57. .131585980987211297340476559160
3. .141440187913335493044362044266 -60. .242963861323419873464620920193
3. .148089166195648547091240358821 -63. .330424615971117653494015036341
3. .155079831711014066219426875291 -66. .320242530479022522819278386712
3. .162453673394142079816996918932 -69. .212343842145151131545629978056
3. .170263238435803653321251051278 -73. .914817829532384218870897241231
3. .178576950387143218445580971263 -76. .239447944328879252547145151558
3. .187487098312147851762837345910 -80. .347869931092452716273904890754
3. .197124048364809100132716198896 -84. .246961458425111728229723378173
3. .207684016171302069889685315347 -89. .70766962048912137685985872969
3. .219491077097820058448943957802 -94. .597709189279271890888632930122
3. .233167498218730742446560147289 -100. .816953473731773843449712310027
3. .250322043032057665569769720213 -107. .391155135378519137796391459762

TWO.SPE (data input file)

```

5 5 0 .....1
  1.0 12.0 25.0 37.0 49.0 .....2
  5.0 15.0 30.0 45.0 60.0 .....3
  1.0 3.0 4.0 6.0 7.0 8.0 9.0 10.0 16.0 18.0 25.0 27.0 .....4
0.032 59.40 00.0 .....5
32.0 0 50 39 .....6
  0.55 70 0.25 0.25 0.25 0.25 .....7
1 2 -1E7 .....8
-1E7 20 15 50 10 .....9
1 7.0 0.0 50.0 75.0 0.0 -80 -180 .....10

```

Example: data input for 1-D uptake (more detailed in section 4.2)

- 1... NX, NZ, NT (Number of x, z and t coordinates)
- 2... x coordinates (Distance from a source in horizontal direction in cm)
- 3... z coordinates (Distance from a source in vertical direction in cm)
- 4... t coordinates (NT = 0 for steady-state case, in day)
- 5... ALPHA (α in cm^{-1}), XKO (K_0 in cm day^{-1}), XLK (k) (k only for time-dependent case)
- 6... QS (Strength of source in $\text{cm}_2 \text{ day}^{-1}$), D (Depth of source in cm), SPCLIN (Spacing of lines in cm), NLINE (Number of lines)
- 7... U (1-D uptake rate in $\text{cm}^2 \text{ day}^{-1}$), DS (Depth of sink or root zone in cm), Uptake rate in 4 fractions (i=1 to 4) and equal for 1-D uniform uptake
- 8... Use only for cyclic case (Wet and Dry cycles)
- 9... Use only for strip uptake
- 10.. Contour plot options

TWO.OUT (Output file)

```

-----
TWO-DIMENSIONAL UNSATURATED FLOW
-----
NLAGUERRE      68

NX NZ NT      5      5      0

  X VALUES    1.000000    12.000000    25.000000    37.000000
    49.000000
  Z VALUES    5.000000    15.000000    30.000000    45.000000
    60.000000
  T VALUES

ALPHA XKO XLK  3.200000E-02    59.400000    90.000000

QS,D,SPCLIN,NLINES    32.000000    0.000000E+00    50.000000

U DS UF(1),(2),(3),(4) 5.500000E-01    70.000000    2.500000E-01
    2.500000E-01    2.500000E-01    2.500000E-01

WETCYC,DRYCYC,HEADINI    1.000000    2.000000    -1.000000E+07

VALUES OF I,QSTRIP(I),XSTRIP(I),ZSTRIP(I), SPCSTRIP(I),NLSTRIP(I) FOLLOW:
NUMBER OF STRIP SINKS USED -->    0

CONTOUR,WIDTH,X1MIN,X1MAX,X2MIN, X1MAX, CONMAX,CONMIN    1.000000
    7.000000    0.000000E+00    50.000000    75.000000
    0.000000E+00    -80.000000    -180.000000

STEADY STATE
-----
T = 0.000000E+00

H VALUES FOLLOW
Z\X  1. 12. 25. 37. 49.
    5. -143. -161. -171. -162. -144.
   15. -159. -164. -170. -165. -159.
   30. -174. -175. -176. -176. -175.
   45. -189. -188. -188. -188. -192.
   60. -201. -202. -202. -202. -203.

```

(Note: Soil water pressure head in -cm)

TWO.COL (Output file in column format)

COLUMNS ARE REAL T,X,Z,H

.0	1.0	5.0	-143.1
.0	12.0	5.0	-160.8
.0	25.0	5.0	-171.1
.0	37.0	5.0	-162.4
.0	49.0	5.0	-144.1
.0	1.0	15.0	-158.5
.0	12.0	15.0	-164.3
.0	25.0	15.0	-169.9
.0	37.0	15.0	-165.2
.0	49.0	15.0	-159.2
.0	1.0	30.0	-173.6
.0	12.0	30.0	-174.9
.0	25.0	30.0	-176.1
.0	37.0	30.0	-176.3
.0	49.0	30.0	-175.1
.0	1.0	45.0	-188.5
.0	12.0	45.0	-187.9
.0	25.0	45.0	-188.5
.0	37.0	45.0	-188.3
.0	49.0	45.0	-191.8
.0	1.0	60.0	-200.7
.0	12.0	60.0	-201.7
.0	25.0	60.0	-202.1
.0	37.0	60.0	-202.4
.0	49.0	60.0	-202.9

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