Dissertation

Salinity Management under a Trickle Irrigation System

Submitted by
Mohamed Ali Rafeet
Chemical and Bioresource Department of Engineering

In partial fulfillment of the requirements
for the Degree of Doctor of Philosophy
Colorado State University
Fort Collins, Colorado
Spring 2002

UMI Number: 3053444

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

COLORADO STATE UNIVERSITY

March 21 2002

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY MOHAMED ALI RAFEET ENTITLED SALINITY MANAGEMENT UNDER A TRICKLE IRRIGATION SYSTEM BE ACCEPTED AS FULFILLING IN PART THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

Ramchand Oad

Adviser

Co-adviser

Department Head

ABSTRACT OF DISSERTATION

SALINITY MANAGEMENT UNDER A TRICKLE IRRIGATION SYSTEM

The aim of this study was to investigate the effects of trickle (drip) irrigation management under saline conditions on sweet corn. The study concentrated on two main factors: amounts of irrigation water and irrigation frequency, either in the field or the Hydrus –2D model. The study objectives were to determine the optimum irrigation configuration to reduce the hazards of salinity in order to increase crop production and to use the model to predict the optimal trickle irrigation management for sweet corn and other row crops. To reach these objectives, measurement data from an experimental field was compared with data from the model based on the field conditions. Additionally, water use efficiency (WUE) and relative yield (RY) were investigated.

The study area was 820 m^2 irrigated by a trickle irrigation system at the Horticultural Experimental Station in northeast Fort Collins, Colorado. The experiments were carried out for two growing seasons (1999 and 2000). The irrigation water application rates were 100%ET, 116%ET, and 124%ET during the 1999 growing season with 3 and 7 day intervals between the irrigations, and 100%ET, 115%ET, and 130%ET during the 2000 growing season with 2 and 7 day intervals between the irrigations. During the growing season, soil samples were taken from different depths under the

emitters and midway between the emitters. The soil samples were taken three times: at the beginning, mid-season, and the end of the season immediately after harvest to estimate electrical conductivity in the active root zone. Salt accumulations simulated by the model for the same field conditions at the same depths were compared with field measurements. Therefore, 72 additional treatments were simulated by the model to estimate the ratios of actual transpiration and potential transpiration (Ta/T_P). From these ratios, expected relative yield (RY) was calculated.

The field results indicated that the greatest amount of accumulated salt occurred under deficit (100%ET) irrigation treatments, and the lowest level of accumulated salt tended to occur under the highest amounts of irrigation water treatments for both seasons. However, the100%ET treatments produced the greatest values of WUE, whereas, the 116%ET and 115%ET resulted in the highest values of RY for both seasons. In general, good agreement between the observed and simulated data on salt distribution was found under the small spaces between the emitters and laterals. Even greater agreement occurred vertically under the emitters compared with the horizontal direction midway between the emitters and lateral tubes. In the simulated treatments simulated using the model, the model produced the greatest values of Ta/Tp and RY under short term irrigation intervals compared with longer irrigation interval. The closer the space between the emitters, the greater the values of Ta/Tp and RY.

Mohamed Ali Rafeet
Chemical and Bioresource
Department of Engineering
Colorado State University
Fort Collins, CO 80523
Spring 2002

ACKNOWLEDGEMENTS

I would like to extend my deep gratitude and appreciation to my adviser, Dr. T. H. Podmore and co-adviser, Dr. G. Cardon for proving guidance and assistance throughout the project. I thank the other committee members, Dr. R. Oad, and Dr. J. Davis for their suggestions and thoughtful review of this work. Special thanks to Dr. G. Butters for his help and input.

Thanks also to my parents and all members of my family for their constant encouragement and their prayers. They are always there when I need them. May Allah bless them with health and happiness for many years to come. My deepest thanks go to my brother Said, and my small family for their encouragement and support throughout this work.

Finally, I would like to thank the government of Sultanate of Oman, Diwan of Royal Court, for providing me with financial support and a scholarship. Without it I would not have been able to pursue my study in the United States.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Salinity is one of the biggest problems in agricultural areas in many countries. This phenomenon is more severe in arid and semi-arid regions that suffer from a shortage of water resources. High rates of salt in the soil or in the irrigation water affect crop productivity, but successful irrigation management can reduce the effects of the salt on crop production, the environment and ground water (Abu-Awwad, 1995).

It seems necessary to reevaluate the scope of management practices and technologies available for salinity control. These include different irrigation systems and scheduling (interval and quantity), leaching fraction and frequency of leaching, selection of tolerant crops and agronomic practices (Rhoades, 1990).

Irrigation scheduling is one of the major parts of irrigation management (commonly defined as determining the timing and amount of irrigation water to be applied to a given crop area). The irrigators decision will vary depending on the following factors: 1) maximum economic return, 2) maximum yield per unit area, 3) maximum yield per unit of water, 4) minimizing the majority of the salinity effects in the crop root zone, and 5) reducing the leaching of chemicals from the root zone to groundwater (Dasberg, and Or, 1999). In regions that have limited water resources, modern irrigation systems such as trickle (drip) irrigation can make better use of a limited water supply. These methods have high application efficiencies, and if a good irrigation management strategy is used they provide more opportunities to control the effects of salinity on crop production compared to traditional irrigation methods. On the other hand, poor management of irrigation systems can diminish their benefits and, consequently, reduce crop production.

Trickle irrigation systems are becoming more popular, especially in places that suffer from a shortage of water. Most of the advantages of trickle irrigation systems, such as high application efficiency and distribution uniformity, are related to the effectiveness of these systems during the irrigation season. These factors change with climatic conditions, soil conditions, social tradition, water availability, and management strategy. Nightingale et al. (1991) concluded that water conservation in arid regions could lead to soil salinity problems, requiring special management strategies to reduce salinity effects.

Although there has been some progress in understanding trickle irrigation management under saline conditions, the interaction between irrigation scheduling and leaching requirements has not been completely elucidated. However, the opportunity to control the amount of irrigation water that leaches from crop root zones, maintain water content to reduce the effects of osmotic pressure around the active root zone, and maximize the water use efficiency are the most important goals of irrigators. Moreover, simulation models are still needed to predict the mobility of chemicals in the unsaturated soil near the surface. Models such as Hydrus-2D will help irrigators make their decisions about trickle irrigation management in the future.

1.1 Problem definition

Salinity management under a trickle irrigation system is very important especially when using saline irrigation water. Salinity management requires an understanding of how salts accumulate and how to use saline water. Salinity management also requires an understanding of how cropping and irrigation activities affect soil and water salinity. Salinity problems are increasing day-by-day because of poor irrigation management practices, and they are more severe in arid conditions. Under salinity and water scarcity conditions, the variation in crop production is related to the amount of salt in the soil or irrigation water that can cause high soil water potential in the root zone, the form of irrigation system, and irrigation management. So, irrigation should supply water at sufficient levels to satisfy crop evapotraspiration demand by maintaining the high matric and osmotic potential of the soil water, which minimizes water and osmotic stresses. In order to achieve this goal of high matric potential, the water content should be kept as high as possible without causing aeration problems.

Trickle irrigation is the system that was used to investigate the previous goals. However, the success of the trickle system depends on the soundness of the management of the system. Trickle irrigation is widely used in regions that have limited irrigation water, therefore, it is important to study irrigation management strategies under saline conditions. Dasberg and Or (1999) summarized the most powerful factors that increase the efficiency of trickle irrigation under salinity conditions as:

The increase in salts and the concentration of the solution resulting from drying between two successive irrigations is less in high frequency irrigation systems than in traditional low frequency irrigation systems, salts from the wetted section are continuously leached from the active root zone and foliar absorption of salts and leaf burn are avoided under trickle irrigation.

Few studies have been done on leaching frictions and irrigation frequencies under drip irrigation in some areas of the world. However, research has not been done on trickle irrigation management under saline conditions in Northern Colorado. Therefore, the contribution of this research is evaluation of leaching requirements, potential evapotranspiration, and irrigation frequencies under Northern Colorado conditions. This study focused on the feasibility of thorough conjunctive management of leaching requirements and irrigation frequency under trickle irrigation on sweet corn (Zea Mays.call. Maple).

Russo and Bakker (1987) stated that the flow regimes pertinent to trickle irrigation requires the development of conceptual simulation models with general applicability for optimal management. In this study, comparisons between the salt concentrations at different levels in the root zone from the field experiment and the numerical model (Hydrus-2D) calculations were investigated to determine whether the model's predictions could be used for trickle irrigation management of sweet corn. The results of the comparisons will help irrigators estimate the amount of irrigation water and the time interval (days) between the irrigations for sweet corn. Moreover, those two factors (the amount of irrigation water and time interval (days) estimated by the model) will save water, decrease the effects of soil and water salinity in the root zone, and maximize crop production. It is expected that different leaching requirements and irrigation frequencies will affect salt accumulation in the root zone of the crop. Moreover, they may result in different levels of crop yield.

1.2 Objectives

The overall objective is to investigate the effects of trickle irrigation system management on salt movement in the active root zone.

Specific objectives are as follows:

1- To investigate the effect of leaching requirements on salt accumulation in both the horizontal and vertical directions;

2- To investigate the effects of irrigation frequencies on salt accumulation both horizontally and vertically;

3- To study crop response to combinations of different leaching fractions and frequencies;

4-To compare the fresh yield production of different treatments with Maas and Hoffman (1977) and Keller and Bliesner (1990) models;

5- To compare the HYDRUS_2D model (Simunek et al., 1999) calculations of salt distribution in two dimensions under different management strategies with the experimental field data;

6- To use the model to determine the optimum system configuration to maximize yield; and

7- To estimate the water use efficiency (WUE) of the crop under each treatment.

CHAPTER 2

LITERATURE REVIEW

2.1 Trickle irrigation

Bucks and Davis (1986) defined trickle irrigation as the slow application of water above or below the soil by surface or subsurface trickle, bubbler spray, or mechanical move and pulse system. Water is applied as discrete or continuous drops through emitters or spray applications placed along a water delivery line near the plant. The shape or design of the emitter reduces the operating pressure from the supply line, and a small volume of water is discharged at points through the soil.

El-Gindy et al. (1990) defined the newest of all commercial methods of water application as a system where water and fertilizer are applied directly to a part of the plant root zone. Water is applied frequently, often maintaining favorable soil moisture stress in plants by maintaining favorable soil moisture conditions. In drip irrigation, water is applied to the soil through mechanical devices called emitters or drippers located at selected points along the lines. Most emitters are placed on the ground, but they can be placed under the soil surface. The emitters dissipate the pressure from the distribution system, so that the energy of the water at the application point is equal only to its potential energy and has essentially no velocity upon leaving the discharge device.

Dasberg and Or (1999) defined trickle irrigation systems as the application of water through point or line sources (emitters) on or under the soil surface at a small operating pressure (20-200 kpa) and a low flow rate (1 to 30 l/hr) per emitter, and this micro-irrigation differs from other systems by the fact that only part of the soil surface is wetted. However, they specified four powerful attributes of trickle irrigation systems compared with traditional irrigation: (1) the total quantity of water applied, (2) the amount applied per unit of wetted area, (3) the plant water use (disregarding frequency of application or surface wetting patterns), and (4) the yield response. They stated that increased yields were related to high water use efficiency, lower water losses due to decreased evaporation, runoff and deep percolation, and less fluctuation in the soil, which avoids water stress in the root zone. However, Phene et al. (1995) summarized some limitations of the trickle irrigation system as follows: salinity hazards under poor irrigation management, a higher management level required than with other irrigation systems, emitter clogging, and high fixed costs.

Hutmacher et al. (1995) related the interest in using a trickle irrigation system to the increasing cost of irrigation and limited water supply, potential for improved water and nutrient application uniformity, potential for improved yields and quality, and the greater ability to control the deep percolation losses of water and solute nutrients.

El-Gindy et al. (1990) summarized the advantages of trickle irrigation as follows:

1- Smaller water resources can be utilized as drip irrigation requires roughly half the water needed by sprinkler or surface irrigation;

2- Lower operation pressures and lower flow rates are required, so less energy is needed for pumping;

3- Labor and operating cost are generally less;

4- Fertilizers can be injected into the irrigation water during the network, and since water is delivered only near the plant, less fertilizer is needed;

5- Less weed growth since only a fraction of the soil is wetted;

6- Frequent or daily applications of water dilute the salt in the soil or leach it out of the root zone, making the use of saline water practical;

7- Field operations can be continued during irrigation as only a limited area around the plant is wetted;

8- Soil crusting is minimized;

9- Disease and insect damage could be reduced because leaves are not wetted;

10- Increased yield and quality of crops due to maintenance of high average soil water content.

Phene et al. (1995) reported that drip irrigation has been demonstrated to improve crop productivity, reduce energy, improve irrigation efficiency, and reduce water loss by deep percolation. However, they also pointed out the following problems, which can be expected with drip irrigation:

1- Emitter clogging is considered the most serious problem in drip irrigation. The causes of clogging are attributed to physical, chemical and biological factors. When clogging occurs, emission uniformity is greatly reduced, and crop damage may occur before the clogging is detected;

2- Higher initial costs compared with surface or portable sprinkler irrigation systems;

3- Drip irrigation is not suitable for closely spaced crops such as cereal grains and alfalfa;

4- A higher level of management is required than with other irrigation systems;

5- Rodents, coyotes, etc, present a problem by damaging the plastic pipes;

6- Salinity hazards under poor drip irrigation management. The accumulated salts on the soil surface and toward the fringes of wetted soil may be leached into the root zone causing detrimental effects; and

7- The fact that a large area of soil surface may receive no water would result in dust formation during mechanical operations.

2.2. Irrigation requirements and irrigation scheduling

The main objective of irrigation is to provide plants with sufficient water to prevent stress that may cause reduction in yield quantity and quality. The required timing and amount of applied water is governed by the prevailing climatic conditions, crop and stage of growth, soil moisture holding capacity and the extent of root development as determined by type of crop, stage of growth, and soil properties (Burman et al., 1983).

Crop water requirements are defined as the depth of water needed to meet the water loss through evapotranspiration (ET-crop) of a disease-free crop growing in large fields under non-restrictive soil conditions, and achieving full production potential under the given growing environment. To calculate ET-crop, three factors are considered: 1) the effect of climate on crop water requirements, which are given by the reference crop evapotranspiration (ETr); 2) the effect of crop characteristics on crop requirements, which are given by the crop coefficient (Kc); and 3) the local conditions and agricultural practices which affect crop water requirements, including the local daily climatic variations, soil water availability, salinity, method of irrigation and cultivation methods and practices (Doorenbos and Pruitt, 1984).

Irrigation scheduling is commonly defined as the determination of when to irrigate and how much water to apply, or as deciding when to start and stop irrigating. Successful irrigation depends upon understanding and utilizing irrigation scheduling principles to develop a management plan, and then on efficiently implementing the plan (Heermann et al., 1990). Heermann et al. (1990) reported that irrigation scheduling is a key element to proper management of irrigation systems. The goal is to apply the correct amount of water at the right time to meet management objectives. The objective may be to maximize irrigation water efficiency, crop production, or economic return or to minimize irrigation costs. Irrigation schedules can be as simple as a rotation based on water availability or as complex as scheduling trickle irrigation systems to deliver water on demand. Field observation of soil water status, plant water status, water budgets and combinations of these factors can be used to schedule irrigation. The water budget can be based on real meteorological data or average climatic data. Irrigation scheduling must be integrated with the total management including energy, labor and cultural practices. Sammis and Wu (1985) presented a method to analyze the effect of drip irrigation management and design on yield including manufacturing uniformity, plugging as it affects uniformity, and irrigation application amounts as related to maximum evapotranspiration. Irrigation application should increase until the marginal value of water equals the marginal value of yield, or until no yield reduction occurs in any part of field. Rainfall, when occurring in small, frequent amounts, decreases the amount of required irrigation water and decreases the effect of the drip irrigation on salt distribution in the active root zone.

2.3 Nature of agricultural salt problems

2.3.1 Salinity constituents and parameters

Tanji (1990) and Homaee (1999) defined salinity as the concentration of dissolved mineral salts present in waters and soils on a unit of volume or weight basis. They divided the major solutes comprising dissolved mineral salts into two groups: cations such as Na, Ca, Mg, and Ka and anions such as CL, SO_4, HCO_3, CO_3, and NO_3. Other components contributing toward salinity in hypersaline waters include B, Sr, Li, SiO_2, Rb, F, Mo, Ba, and AL. However, salinity is expressed in a number of ways, depending on the method and objective of the measurements. Tanji (1990) stated the common terms that salinity can be reported in are mol/l, mg/l (ppm) for major solutes, or in electrical conductivity (EC) in (dS/m) which is the most common method.

2.3.2 Sources of salinity

Tanji (1990) specified the sources of salts in three categories: 1) the primary source of salts in waters and soils is the chemical weathering of earth materials, such as minerals that are constituents of rocks and soils; 2) natural secondary sources of salts include atmospheric deposits of oceanic salts along coastal areas , seawater intrusion into ground-water basins in coastal areas due to overdraft, saline water from rising ground waters, inland saline lakes, and leaching of saline land forms; and 3) anthropogenic sources of salts including irrigation and drainage waters, soil amendments, animal manures and wastes, chemical fertilizer, sewage sludges and effluents, and oil and gas field brines. Shainberg and Shalhevet (1984) stated that the sources and mechanisms of the most important cations in the absorbed and liquid phases are predominantly Ca, Mg, Na, and K. These ions may enter the soil solution through: 1) waters containing salts by surface irrigation or ground water evaporation; 2) fertilizers; 3) weathering of primary and secondary minerals in soils; 4) ion hydrolysis; and 5) organic matter decay.These salts influence plant growth by osmotic effects, specific toxicity effects, and changing the physiomechanical properties of the soils. However, Shainberg and Shalhevet (1984) concluded that the effect of each source depends on the type of agricultural management.

2.3.3 Salt affected soils

Tanji (1990) stated that the suitability of a soil for cropping depends greatly on the degree to which it conducts water and air (permeability) and on physical properties that control the friability of the seedbed (tilth). Poor permeability and tilth often are major problems in irrigated lands. Saline soils generally have normal physical properties. However, sodic soils, may have negative physical properties such as slaking of aggregates and swelling and dispersion of clay minerals, leading to reduced permeability. In soils containing high proportions of Ca and Mg relative to Na or high concentrations of total dissolved electrolytes (saline soils), the exchangeable cation envelope is the cation compressed toward the clay surface. Consequently, the repulsive forces between the like charged envelopes decrease, and the particles can approach closely enough to permit their cohesion into aggregates which yield a matrix of greater pore size compared to individual particles. Therefore, the permeability of aggregated soil is better than that of non-aggregated soil. Pratly and Robertson (1998) concluded that the dispersion of clay in sodic soils leads to structural deterioration, and once dispersed, the affected soil horizon is likely to form a hard surface crust or a hard subsurface layer on drying, which could reduce infiltration of water and air and limit the growth and development of plant roots. Moreover, the dispersion is the release of individual clay platelets from aggregates, and the breakdown of aggregates into sub-aggregate assemblages which can occur at exchangeable sodium percentage (ESP) values of lower than 15 if the electrolyte concentration is low. Dispersed platelets or slaked sub-aggregates can lodge in pore interstices, reducing permeability. Slaking also decreases porosity, which leads to crusting, reduced permeability, and poor tilth.

Szabolcs (1989) summarized the features of some of the more common salt-affected soils into the following categories: saline, sodic, magnesium, and acid sulfate soils. Also, Szabolcs (1989) summarized the aspects of the four categories as illustrated in Table 2.1.

A common problem with salt-affected soil (sodic soil) is reduced percolation of the irrigation water. The porosity of the soil becomes less and some soils can become completely impermeable. Soils become impermeable by two mechanisms: swelling of clay which reduces pore sizes but is not caused by salt, and dispersion of the soil. In those cases (swelling and dispersion), the aggregates break down and smaller minerals move with water and plug the pores, reducing any flow through the soil. Those mechanisms automatically reduce the hydraulic conductivity or infiltration, which will create problems for crops growing in these land.

2.3.4 Salinity effects and distribution

The problems of salt-affected soil are ancient, but their magnitude and their intensity have been increasing in recent decades due to large-scale efforts to bring additional areas under irrigation. The problems have been made worse by development of irrigation systems without adequate provision for drainage and are further being aggravated by poor water management practices and unsound reclamation procedures. The world as a whole is losing at least ten hectares of arable land every minute, three of these from soil salinization.

Table 2.1. Grouping of salt affected soil

Major electrolytes Causes salting problem	Type of salt affected soil	Main effect On production	Method of reclamation	EC (dS/m)	Exchangeable sodium Percentage [A] (ESP)
Any cation and anion particularly sodium magnesium Chloride sulfate	Saline	High osmotic Strength of solution may also be toxic	Removal of Excess salt by leaching	>4	<15
Sodium ions Causing	sodic	Alkaline pH, structural breakdown reducing root penetration, water infiltration and aeration	Replacing sodium with calcium	<4	>15
Magnesium ions NA	Magnesium	Toxic effect, high osmotic strength of the soil solution	Chemical amendment calcium	<4	NA
Ferric and aluminum ion (mainly from sulfate)	Acid sulfate soils	Strong acid producing toxicity	Liming	NA	NA

[A] saturated paste extract, NA; not applicable; Source adapted from Szabolcs, I. (1989).

However, nearly 50 percent of irrigated land in arid and semi arid regions has some degree of soil salinization problems (Abrol et al., 1988). Black (1968) stated that in the United States, salinity and excess sodium reduces the productivity of over one-fourth of the 33 million acres under irrigation. Campbell et al. (1986) stated that about one-third of all irrigated areas in arid and semi-arid regions suffered seriously from salinity, which affects and often significantly decreases crop yield. Hoffman et al. (1983a) related the major threat of salinity in irrigated agriculture to the soils and irrigation waters that contain significant amounts of dissolved salts. They found that limited crop production on about 25 percent of irrigated land in the western United States was related to osmotic effects, individual ion toxicities, or reduced soil permeability caused by excess sodium. Beltrao and Ben Asher (1997) stated that the movement of salts in the soil is dependent on the water movement in the soil, and they concluded that the effect of salinity is effect on the wilting point, thus reducing the available water content. The relative availability of soil water RASW (dimensionless) is affected by soil solution concentration. The wilting point is affected by the solution concentration; the higher the soil solution concentration, the higher the wilting point.

Kruse (1990) stated that the management practices to reduce the effect of salinity, sodicity, and toxicity in the root zone, include:

1- Selecting crops that produce satisfactory yield under salinity, sodicity, and toxicity conditions;
2- Using planting procedures that minimize salt accumulation around the seed;
3- Using land preparation methods that facilitate uniform infiltration of irrigation water;
4- Adopting irrigation procedures to maintain the water content in the root zone;
5- Installing and maintaining drainage systems that facilitate leaching, rooting, and trafficability;
6- Using treatments, e.g., chemical amendments and organic matter, to maintain soil

permeability and tilth;

7- Considering soil properties, water table, and salinity irrigation water.

These procedures are the basic requirements to control salinity and increase crop production.

2.3.5 Effect of trickle irrigation management on salt distribution

Rhoades et al. (1992) reported that salt concentration in the soil increased with depth in the root zone as leaching decreased. The report included two methods that showed how the effect of salt in the root zone could be reduced:

1-Using irrigation methods (such as drip irrigation), which minimize stress in the root - zone.

2-Using high leaching fractions that can also reduce the build up of salt in the root zone.

Oster (1994) summarized the changes that are required with poor irrigation water quality as: 1) selection of appropriately salt-tolerant crops; 2) improvement of water management; and 3) maintenance of soil physical properties to assure soil tilth and permeability to meet crop water leaching requirements.

Nightingale et al. (1985) concluded that the potential effect of trickle irrigation on soil properties should be a primary design factor for trickle irrigation systems with low-quality irrigation water. The success of trickle irrigation, economically and egronomically, is dependent upon sound management of soil salinity and fertility in the crop root zone. Success of solute management under trickle irrigation requires consideration of irrigation water quality, the physical and chemical properties of the soil, and the fertilizer requirements of the crop. On the other hand, Nightitingale et al. (1985)

found that high irrigation frequency was more effective in maintaining a lower salt concentration in the active root zone, because it reduced the effects of osmotic pressure on root water extraction.

Oron et al. (1995) said that saline water could be used under arid and semi-arid conditions if leaching and moisture content are maintained in the root zone, and they related the reasons for using saline water in the future to water shortage problems, a large amount of saline water, and decreasing ground water. The irrigation system that can be adjusted to meet the above conditions is trickle irrigation.

Ayers et al. (1985) found that daily irrigation reduced average salinity in the root zone compared with an irrigation frequency of 3 to 4 day irrigation intervals when using irrigation water that has an EC of 8.5 dS/m. However, Shalhevet et al. (1983) concluded that there was no reduction in yield of eggplant when the irrigation interval was increased from 2 to 12 days with saline as well as non-saline irrigation water. Increasing the interval to 16 days reduced yield significantly with both types of irrigation water.

Pasternak et al. (1995) studied salinity distribution in the root zone of sweet corn for sandy loam soil under trickle irrigation with emitters having a flow rate of 2 l/h. The emitters were located 50 cm intervals and 97 cm between the laterals, and they used brackish water (6.2 dS/m) and fresh water (1.2 dS/m). Two weeks prior to sowing, the field was sprinkler irrigated with 40 mm of fresh water to leach excess salts from previous seasons from the root zone, followed by 60 mm of fresh water applied by trickle irrigation. The brackish water was delivered by trickle irrigation twenty days after sowing. The field was irrigated every second day according to evaporation (Eo) Class A evaporation pan, and the water quantity was raised gradually from 0.4 to 1.0 E_o. The brackish treatments involved 380 mm of brackish water and 100 mm of fresh water. Salinity concentration was measured at depths of 0-30, 30-60, and 60 –90 cm for all treatments. They indicated that the highest concentration of electrical conductivity in occurred at a depth of 0-30 cm and was 6.5 dS /m, and EC were 5.3 and 4.8 dS/m at 30-60 and 60-90 cm, respectively, for the brackish water treatments. Also, the salt concentrations were 2.6, 1.8, and 1.4 dS/m respectively at the previous depths under fresh water treatments.

Russo and Bakker (1987) concluded that the yield depends on both volumetric water content (θ) and EC. On the other hand, they recommended that more research should be done in trickle irrigation systems to model optimal irrigation management.

Abu –Awwad (1995) investigated salt distribution and soil management under trickle irrigated sweet corn by using 1.16, 1.4, 2.2, 3.5, 3.7, and 5.2 dS/m irrigation water for two years and four water amounts: 0.25 (W1), 0.5 (W2), 1.0 (W3), and 1.5 (W4) times evaporation from Class A pan. The soil was a clay (49.9% clay, 25.4% silt, and 24.4% sand), and the average electrical conductivity (ECe) of the soil was 1.9 and 2 dS/m for the first and second years, respectively, for sweet corn which was planted at depth of 5 cm, 15 cm between plants, and 60 cm between rows. The results showed that by increasing irrigation water salinity, the salt in the root zone increased and the maximum amount of salt accumulated at the soil surface and in the water towards the edges of the wetting front. The highest concentration occurred when the applied irrigation water amount was near the crop evapotranspiration (1.0 times evaporation), probably due to non enough applied water to leach the salt out of the root zone. However, the author indicated the importance of avoiding under irrigation with saline irrigation water, and that the concept of trickle irrigation management might be of appreciable benefit for reducing salinity hazards. According to the researcher, the soil water depletion and availability decreased as the average crop root zone or irrigation water salinity increased. The results showed that the average sweet corn yield was increased by increasing the amounts of irrigation water from W1 to W3 in all salinity levels. However, with 3.5 dS/m and above irrigation water salinity, no significant increase occurred in sweet corn fresh ear yields as water amounts increased from W3 to W4.

Hoffman et al. (1979) studied leaching requirements using fiberglass lysimeters (0.80×0.45×0.60 m) in 12 plots, (4.27 m^2) for three crops (wheat, grain sorghum, and lettuce) grown in fine, sandy loam, non-saline soil. The experimental design consisted of six replicated leaching fractions of 17%, 13%, 9%, 4%, and 2% in a field covered by plastic to reduce the effect of rainfall, and the plots receiving irrigation water by trickle irrigation every day at 1350mg/L (an osmotic pressure (π) of 88 Kpa). The result showed no significant reduction below 17% and 9% leaching treatment with sorghum and wheat respectively. However, the lettuce head size, even for the 0.17 treatment was below standard commercial size. Also, yield was not increased above an ET of 440 mm for wheat and 550 mm for sorghum. For lettuce, yield increased linearly as ET increased to 225 mm, but not above 225 mm.

Hoffman et al. (1985) stated that soil salinity was low near the drip tape and high near the surface, midway between emitters. Moreover, they found that salinity decreased using a 25% leaching fraction compared to 15%, but salinity accumulated when using a leaching fraction of 5% for irrigation water with an electrical conductivity of 2.2 dS/m.

Shalhevet and Bernstein (1968) and Shalhevet et al. (1969) found that the soil salinity increased more under large irrigation intervals than under small intervals. Moreover, Ragheb et al. (2000) investigated the salinity distribution under trickle irrigation with 50 cm between the emitters in the same line and 100 cm between the laterals, using 2-day and 4-day irrigation intervals for faba bean varieties. The flow rate of the emitters was 2 L/h and the total amount of irrigation water applied during the growing season was 1500 m^3/fed (375 mm depth and 750 m^3 /fed 179 mm depth) for the 2-day and 4-day irrigation intervals. The electrical conductivity (EC) of the soil surface (0-10 cm) was 1.0 and 1.9 dS/m, respectively, for the 2-day and 4-day irrigation intervals. They concluded that salt distribution in the root zone was affected by both the amount of irrigation water and the irrigation interval.

Singh et al. (1978) reported salt accumulation in the active root zone and midway between the emitters in the same irrigation line and between the trickle laterals. The study showed that the salt accumulated after one season was highest in the surface 15 to 20 cm of soil midway between the emitters and towards the margin of the wetter band at 20 to 30 cm from the crop row. Salt will be removed from, thus, the active root zone the salt would positionally be unavailable for causing injury to plants in all those regions where in-season rainfall does not occur. However, in areas experiencing rainfall during the growing season, the salts accumulated in the soil surface may be expected to be leached and distributed into the zone of active roots in amounts sufficient to injure plants. Obviously, this might impose a limit on the use of brackish water by trickle irrigation.

Using drip irrigation may result in salt accumulation on the soil surface. This depends on soil properties, and irrigation and fertilizer management. By managing the amount of irrigation water and the irrigation interval under a trickle irrigation system, the effect of salt accumulation in the root zone can be reduced. So, special management practices must be developed by considering the interaction between these two factors.

2.4 Crop production under saline conditions

Maas and Hoffman (1977); Hoffman and Van Genuchten (1983); and Hoffman et al. (1990) expressed the effect of salinity on crop yield as a linear response model, and they defined the threshold as the maximum average salt concentration in the root zone that does not cause any yield reduction. However, above the threshold value, the yield declines linearly as salinity increases until the yiel drops to zero as shown in the follwing equation:

$$Y_r = 100\text{-}S\ (C\text{-}C_t),\ C > C_t \qquad (2.1)$$

where

C_t = the threshold (dS/m)

S= the yield fraction decrease per unit of salinity increase $(dS/m)^{-1}$.

C = average salinity at root zone (dS/m)

This model does not consider the effect of water content on yield or an interaction between the amount of irrigation water and electrical conductivity, so this model may be more suitable under high water content availability conditions.

The effect of salt stress on field grown corn was investigated by Maas et al. (1983) and Pasternak et al. (1985). In each case, they concluded that the corn was demonstrated to be sensitive to salt stress at a very early stage. Delaying the commencement of brackish water irrigation until about 3 weeks after planting could avoid crop damage due to salinity sensitivity in the early stage.

Goldberg et al. (1971) indicated that no reduction occurred in sweet corn yield as irrigation water salinity increased from 1 dS/m to 3 dS/m. On the other hand, Maas and Hoffman (1977) found a 25% yield reduction in sweet corn per 2.5 dS/m increase in irrigation water salinity.This differences in result may be because differences in the soil texture, climate conditions, and irrigation management.

Hoffman et al. (1983) stated that for a long-term rhizotron study at the U.S Salinity Laboratory, yield and evapotranspiration of fescue were found be a function of irrigation water salinity, leaching fraction, and irrigation frequency. They demonstrated that increased salt concentration in the irrigation water or decreased leaching fraction resulted in reduced dry matter production and yield. Differences in production under different treatments were related to irrigation frequency and the concentration of salt in the irrigation water. However, by using a high leaching fraction (27%) and irrigation water that had an electrical conductivity of 1 dS/m, annual dry matter yield was 2 kg/m^2 compared to a yield of 1.4 kg/m^2 when a low leaching fraction (9%) and high salinity (4 dS/m) irrigation water were used.

Pasternak et al. (1995) used brackish irrigation water (6.2 dS/m) and fresh water (1.2 dS/m) on 14 sweet corn varieties in sandy loam soil under trickle irrigation. Average relative yield was reduced by 30% when brackish water was used. Moreover, the average yield was 13.5 and 19.1 kg per 10 m^2 for brackish and fresh water respectively. They found the average weight of ears for both types of irrigation water was 275 and 310 grams, and length of kernel rows was 16.2 cm and 17.1 cm for brackish and fresh water, respectively.

Russo and Bakker (1987) stated that using crop water production functions for sweet corn was affected by both the quality and the quantity of irrigation water. They indicated that sweet corn production was reduced by 8% and 27% by using irrigation water with electrical conductivities of 3.6 and 6.7 dS/m, respectively. On the other hand, the highest production was obtained when irrigation water with an electrical conductivity of 1.8 dS/m was used.

2.5 Water use efficiency (Productivity of water use)

Braunworth and Mack (1989) defined water use efficiency as the total crop yield per unit of seasonally applied water (ET) per unit area in silt clay loam soil. Calculation in this value is a direct measure of the productivity a unit of water applied and differs from other indexes of efficiency which are offer expressed as productivity, or performance relative to a standard. They stated that the maximum water use efficiency of fresh-husked ears of sweet corn occurred at an applied rate of 313 mm. On the other hand, the maximum yield occurred at 484 mm water applied. Singh et al. (1978) reported that water use efficiency (WUE) of drip irrigation was nearly twice as high as other methods of water application.

2.6 Soil water and salt regime under trickle irrigation

2.6.1 Water flow mechanism

Water distribution under trickle irrigation was studied by Coelho and Or (1996).

They concluded that the water distribution pattern around a dripper is dependent on 1) total volume of applied water, 2) dripper flow rate and initial and boundary conditions, 3) soil physical properties and their spatial distribition, 4) root activity, and 5) irrigation management. The water flow for one dimension is governed by Richard's equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H}{\partial z}\right] \qquad (2.2)$$

The temporal change in water content q, is stated at any specific flux (cm) at any given point z. This flux is defined by Darcy's law as:

$$q = -K((\theta)\frac{\partial H}{\partial z}) \qquad (2.3)$$

where

K(θ) = the unsaturated hydraulic conductivity, which is a function of water content, and

$\partial H/\partial z$ = the hydraulic head gradient and

H = the hydraulic head, which sum of the gravitational z and the matric (pressure) head (H= h + z)

However, flow under trickle irrigation is applied by emitters, which may be considered as a small circle or point. The water flow equation takes the form of two dimensions as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(\theta)\frac{\partial H}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H}{\partial z}\right] \qquad (2.4)$$

Water uptake can be considered by:

$$\frac{\partial 6}{\partial t} = \nabla . [K(\theta)\ \nabla]\text{-}S \qquad (2.5)$$

where

∇ = the gradient operator, and

S = plant water uptake as a volumetric sink term (volume of water taken up by plant roots per volume of soil per unit time).

$$S = S_{max}/(1+((ah+\pi)/\pi_{50})^3) \qquad (2.6)$$

where

a = acounts for the differential response of the crop to matric and osmotic influences and which is equal to the ratio π_{50} to h_{50},

π_{50} = osmotic pressure at yield reduced by 50%

h_{50} = matric potential at S_{max} and reduced by 50%.

2.6.2 Solutes movement mechanism

Dasberg and Or (1999) summarized the movement of salts in the soil with irrigation water as controlled by three primary mechanisms: convection, diffusion, and mechanical dispersion. In the convective transport (J_c) water and solutes move at the same average rate as the flowing water.

$$J_c = J_w C = C\left[k(h)\frac{dH}{dz}\right] \qquad (2.7)$$

where

C = the volume-average solute concentration,

k(h) = hydraulic conductivity [L/T]

J_c = the solute flux, and

J_w = the water flux (Darcy velocity). The pure water velocity could be estimated by:

$V = J/\theta$, and $J_c = V\theta C$. Convection occurs in the liquid phase only, so $V > J_w$.

The diffusive transport (J_d) is given by Fick's Law:

$$Jd = -Do\frac{dc}{dz} \tag{2.8}$$

where

D_o = the diffusion coefficient in the bulk water. Jury et al. (1991) expressed the relationship between the Do (bulk water) and Ds (soil) as the following equation:

$$D_s = D_o\theta T(\theta) = D_o\theta^{10/3/n2} \tag{2.9}$$

where

D_s [L^2/T] = function of the available path for diffusion determined by the tortuosity $T(\theta)$, resulting from the geometry of the medium (i.e., texture and structure) and

n = porosity. The flux of diffusing solutes in an unsaturated porous medium is thus

$$Jd = -Ds\frac{\partial c}{\partial z} \tag{2.10}$$

a) Dispersive transport (J_h).

Differences in flow velocities at the pore scale (due to different rates, sizes, shapes, and connectivity) cause the solute to be transported locally at different rates and thus lead to mixing (or dispersion) of an incoming solution within an antecedent solution. The solute flux due to mechanical (or hydraulic) dispersion (J_h) is described by an equation similar to Fick's Law for diffusion:

$$Jh = -Dh\frac{\partial c}{\partial z} \tag{2.11}$$

where

D_h = the hydraulic dispersion coefficient [L^2/T], and the coefficient is dependent on the interstitial pore water flow velocity [L/T]and on the dispersivity λ [L] of the soil a function of pore sizes and shapes according to:

$$J_h = \lambda\left\{\frac{J_w}{\theta}\right\}^a = \lambda V^a \tag{2.12}$$

where

a = an empirical factor usually assumed to equal 1 (i.e., a linear dependency of dh on v). The value of λ may range from 1 cm in small columns to a few meters in field experiments. Because of the macroscopic similarity between diffusion and hydrodynamic dispersion, it is common to combine their coefficients (assuming that they are additive) into a diffusion-dispersion coefficient (D_e):

$$D_e(\theta, v) = D_s + D_h \tag{2.13}$$

b) The Convection-Dispersion Equation (CDE) for Inert and Non-absorbing solutes.

The total flux dissolved solutes in soil (J_s) is the result of combined transport by the three mechanisms discussed above, and may be described by the convection- dispersion model:

$$Js = -De\frac{\partial C}{\partial z} + JwC \tag{2.14}$$

where

Js = total mass of solute transported across a unit cross-sectional area of soil per unit time, J_w = the water flux,

D_e = the combined diffusion-dispersion coefficient, and

$\partial C/\partial z$ = the spatial solute gradient. Combining the above equation with the continuity equation yields

$$\partial\frac{6c}{\partial t} = -\frac{\partial Js}{\partial z} \tag{2.15}$$

where

θc = the mass of solutes in solution. So the continuity equation may be written as:

$$\frac{\partial(\theta c)}{\partial t} = -\frac{\partial}{\partial z}\left(JwC - De\frac{\partial c}{\partial z} \right) \qquad (2.16)$$

Assuming a steady state water flow in a homogeneous soil profile (J_w and θ are constant in time and location of sample) reduces the above equation to the familiar form of the convection-dispersion equation (CDE) for inert and non-absorbing solutes:

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - V\frac{\partial C}{\partial z} \qquad (2.17)$$

where

$D = D_e$, and

$V = J_w/\theta$. The CDE may be expanded to describe two and three-dimensional solute movement which used under trickle irrigation sytem:

$$\frac{\partial C}{\partial t} = \nabla . (D \nabla C) - V . \nabla C. \qquad (2.18)$$

where ∇ = gradiant operator.

CHAPTER 3

MATERIALS AND METHODS

3.1 Methodology

In order to achieve the specific objectives of this study, the following methodologies were followed.

1. Investigate the effect of the leaching requirements and irrigation frequency on salt concentration in both horizontal and vertical directions. These two objectives evaluated the influence of different amounts of irrigation water and irrigation intervals on salt concentration in the root zone. To examine these two objectives, soil samples were taken in both directions, horizontally under the emitters and midway between the emitters and vertically from 0 cm to 90 cm below each treatment. The differences in the salt concentration at the different levels were analyzed statistically to estimate the variation of EC between the treatments. From this investigation, the relative LR and irrigation frequency were calculated for sweet corn (Zea Mays. call. Maple) under trickle irrigation. The leaching frictions were calculated by Keller and Bliesner (1990) as:

$$LRt = \frac{EC_w}{2(MaxECe)} \quad (3.1)$$

where

LRt = leaching requirement ratio under trickle irrigation,

EC_w = electrical conductivity of the irrigation water, dS/m.

Max EC_e = electrical conductivity of the saturated soil extract that will reduce yield to zero, dS/m. Moreover, Rhoades's (1974) model was used to estimate leaching requirements (LR):

$$LR = \frac{EC_w}{(5EC_e - EC_w)} \qquad (3.2)$$

where

EC_w = electrical conductivity of the irrigation water, dS/m

EC_e = electrical conductivity of the saturated soil extract, dS/m.

The values that were used for the leaching requirement were estimated for the experimental field data by using Keller and Bliesner (1990) and Rhoades (1974) equations, respectively, and were defined as 16% and 24% of the irrigation water. These two ratios of the leaching requirement were calculated for the initial salt concentration in the experimental field from the soil and irrigation water.

2. *Investigate the crop response by comparing the fresh yield to combinations of leaching requirements and irrigation frequency.*

The third and fourth objectives dealt with the crop yield response to the different levels of leaching requirements and irrigation frequency. They were considering by estimating water use efficiency for each treatment and compared it with the usual field production, which was irrigated by the furrow irrigation method with city water in the same area. For both objectives, the relationship between crop yield and seasonal amount of applied water (crop-water production function) is required to determine optimum irrigation management in three levels of leaching requirements and two irrigation intervals. To investigate those goals, several procedures were done:

1- All of the fresh ears were harvested and sorted into marketable and non-marketable classes, estimated visually and sorted according to USDA grades of sweet corn.

2-The fresh ears were weighed, including the husk, for each treatment and. The comparison between relative yield (RY) for field results of sweet corn yield production was defined by Maas and Hoffman (1977) and Ayers and Westcott (1985) as a percentage. Crop production was related to both models. Maas and Hoffman (1977) conducted many field experiments related to root-zone salinity and they determined the expression for crop yield as:

$$Yr=100-S\,(C-Ct) \tag{3.3}$$

Where

Yr = relative yield (percentage),

C = average root zone salinity (dS/m),

Ct = threshold root-zone salinity where yield reduction occurs (dS/m),

S = percentage yield reduction per unit of salinity increase.

On the other hand, Ayers and Westcott (1985) estimated that the minimum and the maximum values of ECe for sweet corn are 1.7 dS/m and 10 dS/m, respectively. The minimum value does not reduce yield, but the maximum value reduces the yield to zero.

They concluded that the relative yield (Yr) is as follows:

$$Yr = \frac{MaxEC_e - EC_w}{MaxEC_e - MinEC_e} \tag{3.4}$$

Where

Yr = relative yield, which is the ratio of estimated yield affected by saline water and soil to full potential yield under trickle irrigation

EC_w = electrical conductivity of the irrigation water dS/m,

Min ECe = electrical conductivity of the saturated soil extract that will not decrease crop yield, dS/m,

Max ECe = electrical conductivity of the saturated soil extract that will reduce yield to zero (dS/m). Equation 3.4 is used when the quality of irrigation water (ECw) is between the min ECe and (max ECe+min ECe)/2. (Due to the field conditions, the average relative crop yields were 79.3% for Mass and Hoffman (1977) model and 82% for the Ayers and Westcott (1985) model).

3. The comparison between the field experiment result and the model calculation investigated:

This objective concentrated on the comparison between the calculation of the Hydrus-2D model (which measures solute movement vertically and horizontally) and field experimental data. The result of the field experimental data was calculated and compared with the model calculations. Three indicators of agreement between model (simulated) and field result (observed) were been used to compare the field results and the model calculation agreement: root mean square error (RMSE), relative error (RE).

Both RMSE and RE were defined by Ferrer-Alegre and Stockle (1999), and Loague and Green (1991), and the index of agreement (d) (Willmott, 1982):

$$RMSE = \left[\frac{\sum_{i=1}^{N} (S_i - O_i)^2}{N} \right]^{1/2} \tag{3.5}$$

$$RE = \frac{RMSE}{O_{avg}} \times 100 \tag{3.6}$$

$$d = 1 - \frac{\sum_{i=1}^{N} (S_i - O_i)^2}{\sum_{i=1}^{N} \left(|S'_i| + |O'_i| \right)^2} \tag{3.7}$$

where

S_i = simulated value

O_i = observed value

N = number of the data points

O_{avg} = average of the observed values

$S'_i = S_i - O_{avg}$

$O'_i = O_i - O_{avg}$

The value of d varies from 0 to 1, where 1 indicates perfect agreement between simulated and observed values.

4. Predict the optimum system configuration to maximize the yield

This objective is to determine the optimum configuration to maximize the yield and the water use efficiency. The different alternatives of spacing of laterals and emitters, irrigation frequencies and the amount of the leaching requirements were developed to determine the optimum trickle irrigation management for sweet corn. The previous procedures might be done after comparing the recent treatments to consider an agreement between the simulation and observation data. Both cases (the recent and alternative conditions) will be compared to figure the most optimum design and management that has the highest rate of actual transpiration (Ta)and potential transpiration (Tp) and relative yield (RY) to predict irrigation schedules for trickle irrigation for sweet corn under saline conditions in the future.

5. Estimate the water use efficiency (WUE) of crop under each treatment

The last objective, water use efficiency (WUE), which is defined as the ratio of crop yield to the total amount of irrigation water for the crop season, uses the average weight of the fresh ears (Doorenbos and Pruitt, 1984 and Braunworth et al. 1989). According to Doorenbos and Pruitt, and Braunworth et al. water use efficiency is calculated as:

$$WUE = \frac{Y}{IR} \tag{3.8}$$

Where

WUE = water use efficiency (kg/m^3), or kg/ha/mm

Y = Crop production (kg)

IR = amount of irrigation water during the season (m^3).

In all objectives, three types of statistical analysis were used to determine the significant differences for EC concentration in the root zone of the plant at different depths and fresh ear weight for all treatments at the 0.05 level. By definition, this experiment is considered to be a randomized complete block design which could be analyzed as factorial (Ott, 1992).

1- The data are analyzed by using the SAS program (Proc Mixed) to test the significant differences between the treatments and interactions between the treatments at different depths of the profile.

2- Least significant difference (LSD) comparison was used to compare the treatments means of salt concentration and fresh crop yield.

3-The comparison of the weight of fresh un-husked ears for each treatment estimation was used to determine whether there were significant differences between the treatments.

3.2 Field experiment

Field experiments were established on 840 m^2 and conducted for two seasons (1999 and 2000) at the Horticulture Experiment Station in northeast Fort Collins for sweet corn crop (Zea Mays. Call maple). At the beginning of each season, the field was cultivated at 15 to 20 cm depth and mixed with herbicides. The experiment started after the sowing of the crop to investigate the effect of different management strategies of trickle irrigation system under salinity conditions.

3.2.1 Irrigation water

Ground water from the well located in the field was used to irrigate the experimental field. The depth of the water table was measured three times during the irrigation period to estimate whether the water table has any effect on the water content in the root zone. The depth of the water table ranged between 6.7 to 7 m in the beginning and the end of the season for both seasons, respectively. To consider the water table depth, a measuring tape was used as shown in Figure 3.1.

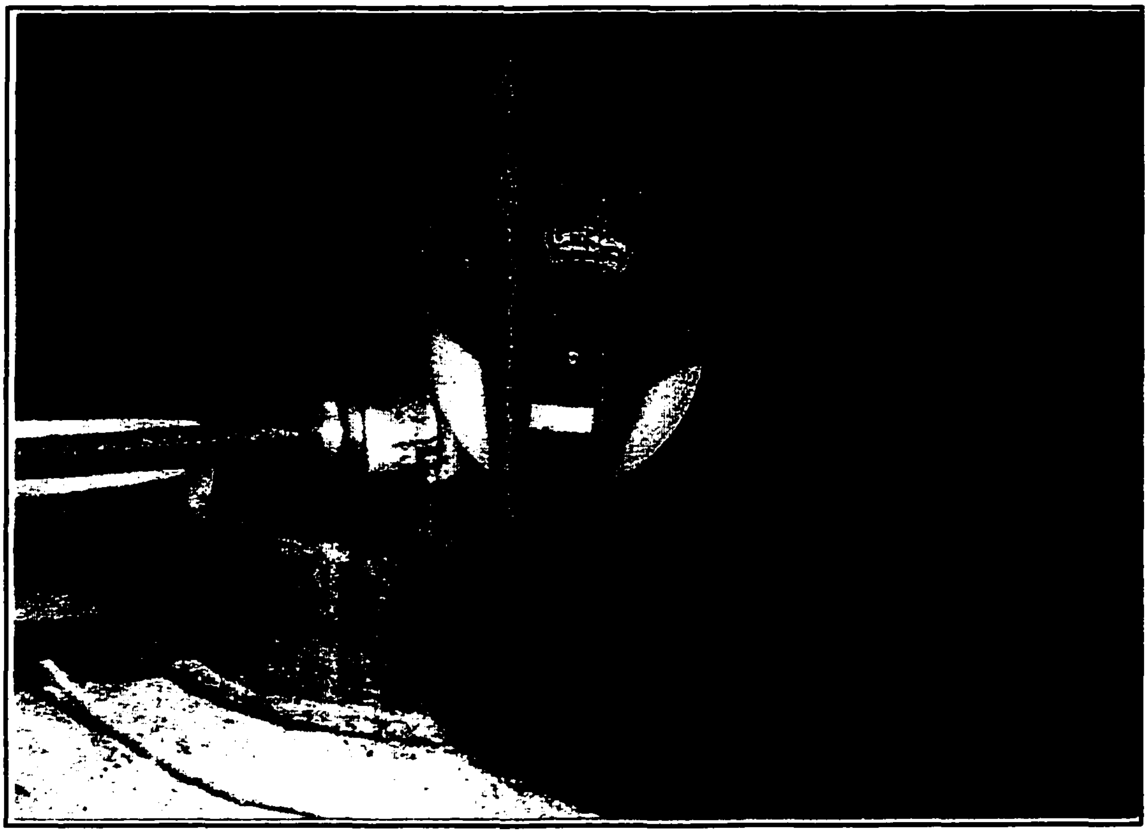

Figure 3.1. Measuring tape inserted into well casing used to determine water table depth.

Irrigation water samples were taken three times during the season to measure electrical conductivity. The electrical conductivity ranged between 3.2 to 3.24 dS/m at the beginning and the end of the season, respectively. The chemical characteristics of the irrigation water were analyzed by the Soil, Water, and Plant Testing Laboratory at

Colorado State University before the experiment began to estimate chemical water properties (Table 3.1).

Table 3.1. Irrigation water chemical characteristics.

Salt	Measurement unit	Value
PH	---	7.5
EC	dS/m	3.2
Calcium	mg/l	376.6
Magnesium	mg/l	175.8
Sodium	mg/l	186.9
Potassium	mg/l	5.9
Carbonate	mg/l	<0.1
Bicarbonate	mg/l	334
Chloride	mg/l	33
Sulfate	mg/l	1676 (lbs of SO_4 per acre foot 1,490)
Nitrate	mg/l	40.8 (lbs of NO_3 per acre foot 25.1)
Boron	mg/l	0.21 NA
Nitrate as N	mg/l	9.2
SAR	--	2.0 (low)
Salinity hazard	---	High

3.2.2 Soil Properties

Before the experiment, soil samples were collected with a soil probe from three depths (0-30, 30-60, and 60-90 cm) at different block locations and were mixed together and averaged. The properties of the soil samples were analyzed by The Soil, Water, and Plant Testing Laboratory at Colorado State University (Table 3.2). Soil texture was specified as clay soil with high salinity in all three depths.

The electrical conductivity of the soil samples was measured three times during both growing seasons at:

1- the beginning of the season (May 17 1999 season and May 12 2000 season)

2- mid-season (August 9 1999 season and August 13 2000 season)

3- the end of the season (Septaber 11 1999 season and September 22 2000 season)

Soil samples were collected from each treatment by using a probe as shown in Figure 3.2. The samples were picked randomly from the center of the experimental units.

Table 3.2. Soil physical and chemical characteristics.

				----------ppm----------						
Depth (cm)	pH	EC (dS/m)	Lime estimate	% OM	NO_3 -N	P	K	Zn	Fe	Mn
0-30	7.8	3.6	high	1.5	37.3	13.8	310	0.89	8.48	7.45
30-60	7.9	3.8	high	1.0	16.6	2.2	242	0.54	7.01	4.16
60-90	7.8	3.9	high	1.1	13.1	1.4	283	0.68	6.72	4.23

	----------meq/l----------					----------%----------			
Depth (cm)	Ca	Mg	Na	K	SAR	Sand	Silt	Clay	Texture
0-30	32.4	15.9	9.7	0.7	2.0	29	13	58	Clay
30-60	29.2	20.1	9.2	2.9	1.9	28	10	62	Clay
60-90	28.4	23.4	8.8	0.4	1.7	30	30	40	Clay/Clay Loam

This procedure was followed to avoid the effect of boundary conditions of plots and to reduce experimental errors. They were taken in horizontal and vertical directions from each plot. The soil samples were prepared and saturated by distilled water to estimate their electrical conductivity, using the saturated extract method developed by the American Public Health Association (1995).

3.2.3 Hydraulic conductivity of the soil

The ordinary tension infiltometer (OTI) is used to measure hydraulic conductivity of soil that is nearly saturated. The hydraulic conductivity is estimated by a disc parameter that was developed by Perroux and White (1988). The design of the ordinary tension infiltrometer (OTI) is presented in Figure 3.3. As shown in Figure 3.3, the commercial model of a disc parameter consists of one reservoir tube, and one bubbling tube, one 20 cm diameter disc wrapped by a piece of nylon screen (called nylon

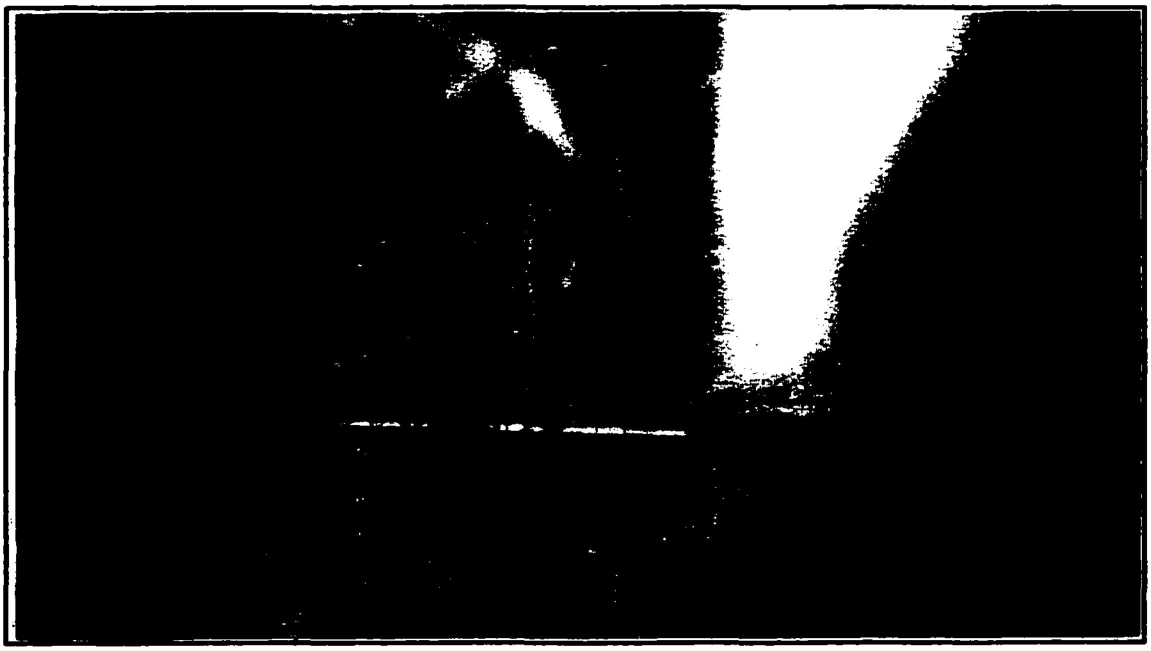

Figure 3.2. Probe used to sample soil at different depths.

membrane) with an air –entry suction head smaller than 20 cm. Both the reservoir tube and bubbling tube are made of clear plastic, and they are removable. Water was applied into the reservoir tube before the measurement started. An imposed head applied to the membrane may be adjusted by changing the water level in the bubbling tube. Infiltration rates of the water were recorded every 5 minutes until steady state was reached.

3.2.4 Crop and fertilizer

Sweet corn (Zea Mays. call. Maple) was grown for this experiment. This crop was chosen because of its sensitivity to salt conditions, its short growing season, and its prevalence as a common crop in Northern Colorado. The crop was planted on ridges with a planter at 15 cm (6 in) between the plants in the same row and 75 cm (30 in) between the rows with plant populations of 88,000 plants ha^{-1}. Plant populations were calculated by dividing 10,000 m^2 by the area taken up by one plant (0.15*0.75 m). The crop was planted on June 20, 1999 and harvested on Sep. 6,1999. In the second season, the crop was planted on June 15, 2000, and fresh ears were harvested on Sep.18 2000. Then the ears were sorted as marketable and non-marketable and weighed. The weight of the fresh ears was compared with the standard ear yield, which was irrigated using the city water by furrow irrigation system under field conditions.

The recommended fertilizer (NPK) rates were calculated using Northern Colorado Fertilizer Manual Recommendations (Soltanpour et al., 1985) during both seasons. The recommendation is dependent on average concentration residual soil NO_3-N, P, and K, and soil organic matter (OM), and a yield goal of 150 bu grain or 30 T silage. Residual (N, P and K) were estimated by analyzing soil samples from the field and in the irrigation water. Residual soil NO_3-N in the root zone (0-120 cm) prior to planting in 1999 averaged 18 ppm, and the average soil OM content at the same depth was 1.2 percent. The residual phosphorus (P) and potassium (K) at the 0-120 cm depth were 5.8 and 278 ppm respectively. Based on these levels of residual soil and water NO_3-N, soil OM, and the yield goal of the recommended N, P, and K, applied rates were 161 kg/ha of N and 56 kg of P/ha. Because of the high rate of potassium residual in the soil, potassium was not added to the experimental field.

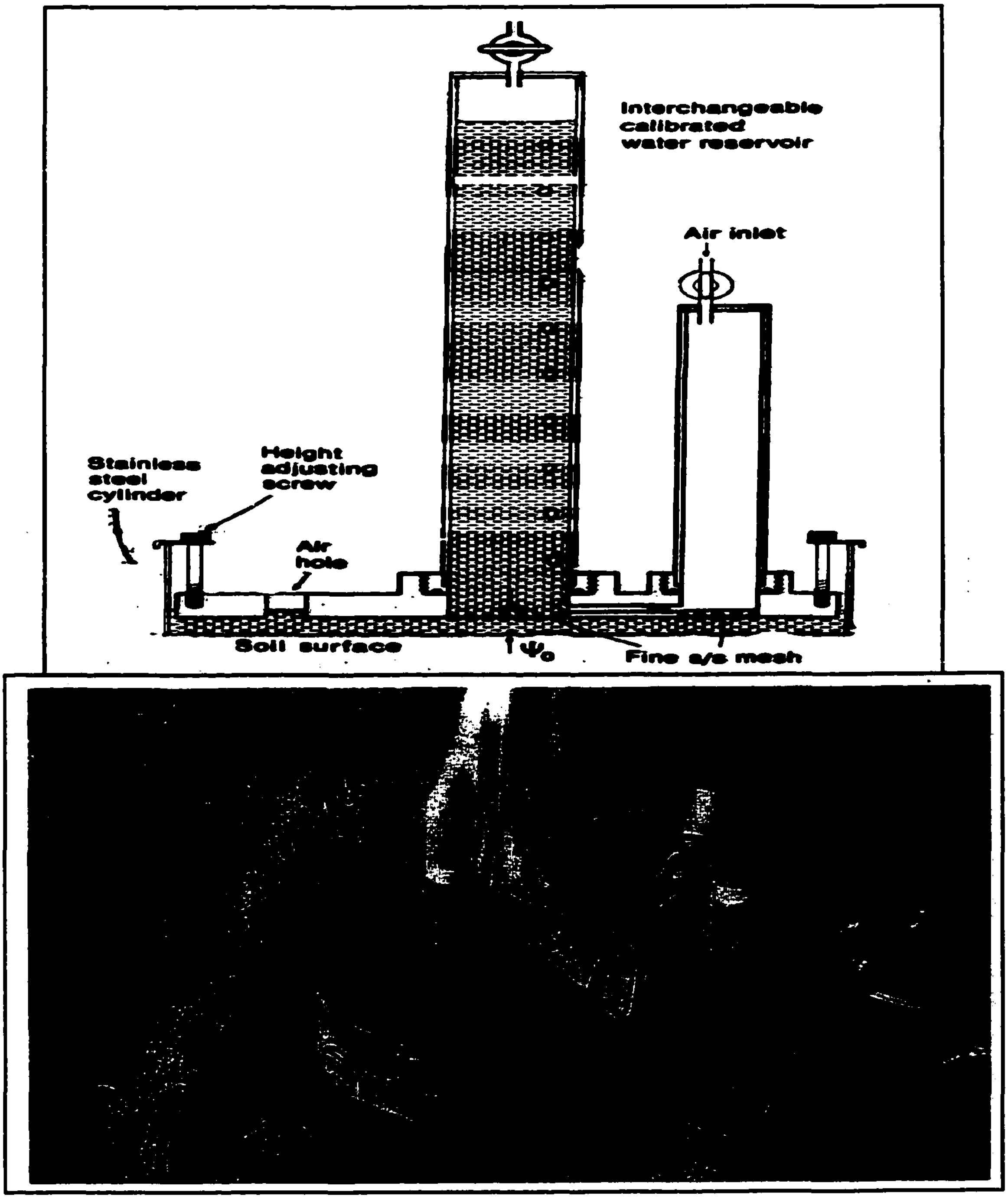

Figure 3.3.The disc permeameter used for infiltration measurements at small positive pressure (devised by Perroux and White 1988).

The amount of fertilizer was fixed for all treatments. Since, the emitters are very sensitive to plugging, liquid fertilizer was preferred to fertilize the crop. The fertilizer (N and P) were injected with water in the trickle irrigation system twice during the season. Moreover, weeds were controlled chemically and by hand. The chemical method used a sprayer to remove the weeds between the rows, but within the rows, the hand method was used to remove the weeds.

3.2. 5 Irrigation system

The trickle irrigation system is one of the most suitable methods of irrigation for arid and semi-arid conditions. The system consists of three stages: design, installation, and management. The management stage started from the beginning of irrigation. The field experiment combined three leaching requirements and two irrigation frequencies. Since there was not enough precipitation at the beginning of the season, the trickle irrigation system was laid out soon after planting as is illustrated in Figure 3.4. The trickle irrigation system consists of a control head (pump, regular pressure, filters, injector, pressure gauge and water meter) followed by a network including a main line, sub-mains, laterals, and emitters.

The emitters' manufacturing discharge is 2.27 L/hr (0.6 gallon/hr), and the distance between the emitters was 15 cm. The irrigation system was calibrated in the field to estimate emitter discharge rate and the pressure uniformity distribution (EU). To reach this goal, the water was collected randomly by beaker for 5 minutes from 20 emitters as shown in Figure 3.5. In addition, the pressure gauge was placed at the end of some lateral tubes in the beginning, mid-season, and the end of the season at each

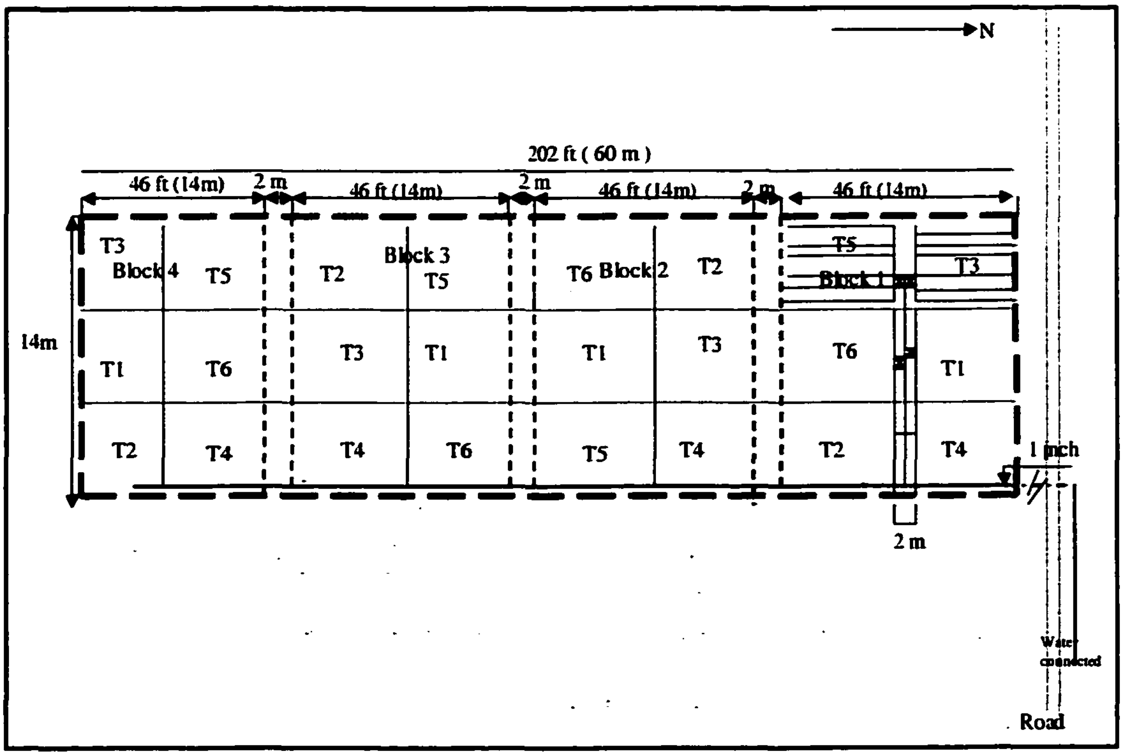

Figure 3.4. Trickle irrigation system design for the field experiment.

Figure 3.5. Collection beaker used to determine discharge and irrigation distribution uniformity of emitters in the field.

experimental unit (treatment) during irrigation as shown in Figure 3.6. The uniformity distribution of the irrigation system was calculated by Keller and Bliesner's (1990) model equation 3.9.

$$EU = 100\frac{q_n}{q_a} \tag{3.9}$$

Where

EU = field test emission uniformity, %

q_n = average rate of discharge of the lowest one-fourth of field data emitter discharge readings, L/hr (gpm)

q_a = average discharge rate of all the emitters that were checked in the field, L/hr (gpm).

Based on the collected data, the irrigation system efficiency was approximately 96%. However, to maintain the uniformity of the irrigation system constant, the system was maintained through out the experimental period. This maintenance procedure was taken

Figure 3.6. Pressure gauge to estimate pressure distribution in lateral tubes.

three times in both seasons, at the beginning, middle, and end of the season, by flushing the irrigation system and increasing the irrigation water pressure for each treatment to move accumulated chemicals and biological parts from the outlets of the emitters.

3.3 Experimental design.

3.3.1 Experimental design and measurements in 1999.

The experiment was laid out in a randomized complete block design for the trickle irrigation system on 840 m^2 as presented in Figure 3.4. The irrigation system had six treatments and four replications. The treatments were as follows:

T1, 24% leaching fraction and irrigated at seven-day intervals

T2, 16% leaching fraction and irrigated at seven-day intervals

T3, 0% leaching fraction and irrigated at seven-day intervals

T4, 24% leaching fraction and irrigated at three-day intervals.

T5, 16% leaching fraction and irrigated at three-day intervals.

T6, 0% leaching fraction and irrigated at three-day intervals.

The amount of irrigation water was estimated as ET-crop, which was obtained from daily weather data from the weather station at the experimental station. The ET-crop was obtained by multiplying the crop coefficient by the alfalfa ETr, calculated on a daily basis using the Kimberly Penman combination (1982) equation. The 24% leaching fraction was estimated by the Rhoades's equation (1974), but the 16% leaching fraction was estimated by the Keller and Bliesner model (1990).

Soil samples were collected in both directions, horizontally under the emitters and midway between the emitters and vertically in three levels: 0-30 cm, 30-60 cm, and

60-90 cm from each plot as illustrated in Figure 3.7. The differences in salt concentration at the different levels were analyzed statistically to estimate the variation of EC among the treatments and within different depths of the treatments.

3.3.2 Experimental design and measurements in 2000.

The experiment was conducted for the second season in 2000 on 840 m^2 at the Horticulture Experimental Station north of Fort Collins. At the beginning of the season, the field was cultivated and mixed with herbicides. The experiment started after the sowing of the crop to investigate the effect of adjusting different management strategies of a trickle irrigation system under saline conditions. The experiment was laid out in a randomized complete block design for trickle irrigation systems. The irrigation system

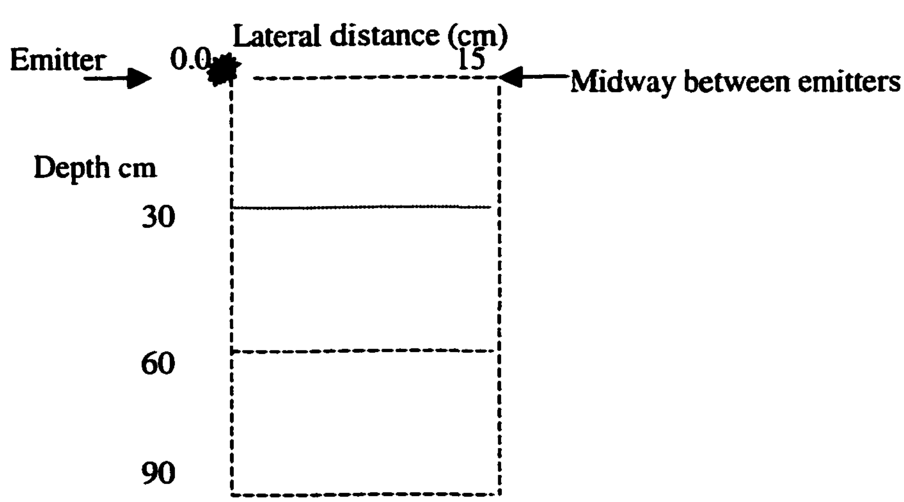

Figure 3.7. Soil samples design under emitters to midway between two emitters for each plot, 1999 season.

had six treatments and four replications. The treatments were as follows:

T1, 30% leaching and irrigation after seven-day intervals,

T2, 15% leaching and irrigation after seven-day intervals, T3, 0% leaching and irrigation after seven-day intervals,

T4, 30% leaching and irrigation after two-day intervals,

T5, 15% leaching and irrigation after two-day intervals,

T6, 0% leaching and irrigation after two-day intervals,

The layout of the experiment is illustrated in Figure 3.4. The crop was planted in rows with 6 inches (15 cm) between the plants and 30 inches (75 cm) between the rows.

Soil samples were taken from each plot in six depth measurements (0-15 cm, 15-30 cm, 30-45 cm, 45-60 cm, 60-75 cm, and 75-90 cm) before laying out the irrigation system in order to estimate some physical and chemical characteristics, such as soil texture and electrical conductivity. The soil salinity was expressed as the electrical conductivity of the saturated extracts for each treatment. The soil samples' EC was considered at different layers of the root zone to follow the salt movement in the active root-zone during the experimental season. In this case, the soil samples were taken from both directions vertically at depths of 0-15 cm, 15-30 cm, 30-45 cm, 45-60 cm, 60-75 cm, and 75-90 cm. Samples were collected under the emitter (0.0 cm) and midway between the emitters (37.5 cm) to analyze electrical conductivity (EC) in the soil. Figure.3.8 shows the method of soil samples that were taken. The irrigation water's electrical conductivity was measured frequently during the season. At the same time, the water table level was measured to determine if it had risen or dropped compared with last year. This procedure was done to determine if rising ground water has the effect of increasing salt concentrations in the root zone of the crop.

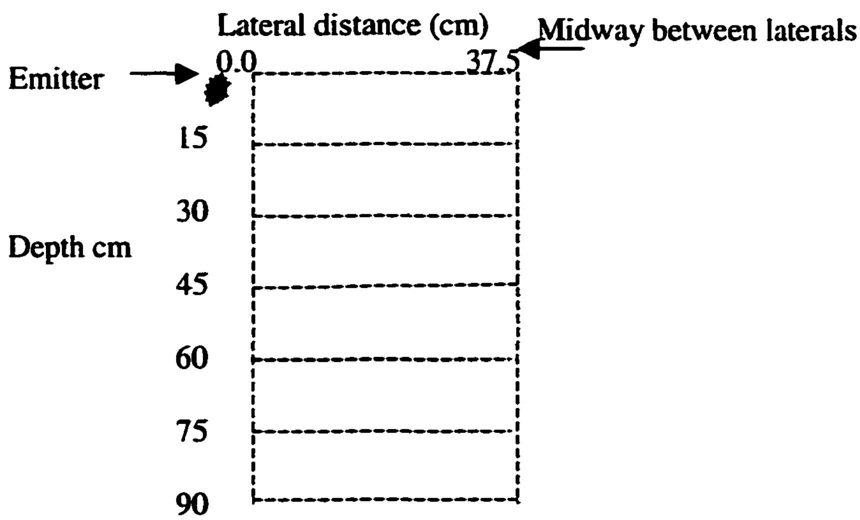

Figure 3.8. Soil samples design under emitters to midway between two lateral tubes for each plot, 2000 season.

3.4 Crop water requirement

The reference evapotranspiration (ETr) and precipitation information were determined using an on-site weather station (Fort Collins East Alfalfa Site Station) in northeast Fort Collins. The (ETr) was calculated on a daily basis by using the 1982 Kimberly Penman combination equation:

$$ETr = \frac{\Delta}{(\Delta + \gamma)}(Rn - G) +)\frac{\gamma}{(\Delta + \gamma)} f(u)(e_a - e_d) \quad (3.10)$$

where

$f(u) = 0.263\ (a_w + b_w u_2)$

Δ = the slope of the saturation vapor pressure curve (mb/k°)

γ = a pychrometric constant (mb /k°)

Rn = is the net long –wave and short-wave radiation, mm/day, water equivalent

G = heat flux into soil mm/day, water equivalent

U_2 = wind speed at 2 m height m/s.

e_a= saturated vapor pressure (mb) at height z above the ground or water surface.

e_d = actual vapor pressure (mb)

a_w = empirical coefficient

b_w = empirical coefficient (Allen, 1986)

To manage and schedule any irrigation system, a crop coefficient has to be considered during the crop growth stages. The growing season is divided into four stages:

1) initial stage, which is the germination and early growth when the soil surface is not covered by the crop (groundcover <10%),
2) crop development stage, which starts from the end of the initial stage to attainment of effective full groundcover (groundcover = 70-80%)
3) mid-season stage, which starts from attainment of effective full groundcover to start of maturation
4) late season stage, which starts from mid-season stage until full maturity or harvest.

The values of Kc for the various growth stages for sweet corn are given below, the ET representative of alfalfa as shown in Table 3.3.

Table 3.3 Sweet corn's coefficient (Kc) for different stages during the growing season (Cuenca, 1989).

Day	1-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55
Kc	0.15	0.16	0.17	0.18	0.25	0.40	0.62	0.80	0.93
Days	56-60	61-65	66-70	71-75	76-80	81-85	86-90	91-95	
Kc	0.93	0.91	0.90	0.88	0.80	0.70	0.50	0.25	

Crop water requirements were based on crop-ET, calculated daily for different crop development stages from the climatic site-station data by equation 3.11

$$ET-crop = Kc \times ETr \tag{3.11}$$

Where

Kc = crop coefficient

ETr = reference evapotranspiration, mm/day

ET-crop = Crop evapotranspiration mm/day

The irrigation water requirements (IR) were based on crop water requirements, irrigation efficiency, and leaching fractions, the calculation procedure for which is given in the following equation:

$$IR = \frac{ET_{-crop}}{Ea} \tag{3.12}$$

where

IR = irrigation requirement (gross water in mm), and

Ea =application efficiency of irrigation system (EU).

Under rainfall conditions, the depth of applied irrigation water required can be affected by the precipitation when the rainfall is effective (P_{ef}). In this case, the irrigation water applied (W) is estimated by using the equation 3.13:

$$W=CWR-P_{ef} \tag{3.13}$$

where

W= irrigation water applied, mm

CWR = crop water requirement including inefficiencies of the application system (IR) and leaching requirements (LR), mm

P_{ef} = effective precipitation (in this case total amount of rainfall), mm (Prendergast, 1993).

The target irrigation treatments in 1999 were 100, 116, and 124% of ET-crop. In 2000 the treatments were slightly modified in relation to the 1999 treatments. So, in 2000 the target irrigation amounts were 100, 115, and 130% of ET-crop. In seasons 1999 and 2000, the precipitation was 78 and 32 mm, respectively. Based on the above conditions, the total amount of irrigation water during the two seasons that was applied soon after planted and before the follow up treatments, by the trickle irrigation system were 184, 206, and 217 mm in 1999, and 262, 284, and 295 mm in 2000. The field was irrigated directly after sowing with 34 mm of water in both seasons. The total amount of irrigated water, including precipitation and the added water, was 100%ET, 116%ET, and 124%ET in 1999 were 296, 318, and 329 mm, respectively. In the 2000 season, the total amounts of irrigation water and precipitation for 100%ET, 115%ET, and 130%ET were 294, 330, 367 mm. The amounts of irrigation water during both seasons are shown in Table 3.4.

3.5 Model

Solute movement in two direction models are complicated compared with one direction movement behavior. Numerical models are usuful solutions to predict solute movement behavior in the active root zone of the crop. Simunek et al. (1993) developed a general-purpose two dimensional numerical model known as HYDRUS_2D. The HYDRUS_2D program numerically solves the Richard's equation for saturated and unsaturated water flow and the convection-dispersion equation for solute transport with some modifications as shown later on in this chapter. The program is based on the finite–elements scheme and incorporates a graphical user-interface for data entry (soil properties, atmospheric conditions, emitter discharge, and boundary conditions). Since solute transport is considered in two

Table 3.4. Target irrigation application, irrigation application, precipitation, 1999 and 2000.

Treatments	1999					
	Target Irrigation application	Irrigation		Precipitation	Total	Irrigation intervals
	%	---mm---				days
T1	124	34	228	78	359	7
T2	116	34	213	78	338	7
T3	100	34	184	78	296	7
T4	124	34	228	78	359	3
T5	116	34	213	78	338	3
T6	100	34	184	78	296	3
Treatments	2000					
	Target Irrigation application	Irrigation		Precipitation	Total	Irrigation intervals
	----%-------	---mm---				days
T1	130	34	296	32	372	7
T2	115	34	262	32	333	7
T3	100	34	228	32	294	7
T4	130	34	341	32	372	2
T5	115	34	301	32	333	2
T6	100	34	228	32	294	2

dimensions under trickle irrigation, the model will be used to compare the agreement between the measurements and calculated values of the solute movement under different trickle irrigation management systems. Hydraulic conductivity at steady state infiltration rate for field experimental conditions within the flow region were specified for the active root zone. Also, initial salt concentration of the soil and irrigation water, evapotranspiration, amount of irrigation water and frequencies, and rainfall were used as the input data for the model to demonstrate model evaluation and prediction procedures.

3.5.1 Governing flow equation

The governing equation for two-dimensional isothermal Darcian flow of water in a variably saturated rigid porous medium, assuming that the air phase plays an insignificant role in the liquid flow process, is considered by a modified form of Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial xi}\left[K(K_{ij}^{A}\frac{\partial h}{\partial xj} + K_{ij}^{A})\right] - S \qquad (3.14)$$

where

θ = volumetric water content $[L^3L^{-3}]$,

h = pressure head [L],

S = a sink term $[T^{-1}]$,

x_i = (I = 1,2) , the spatial coordinates [L],

t = time [T],

K_{ij}^A = components of a dimensionless anisotropy tersor K^A, and

K = the unsaturated hydraulic conductivity function [LT^{-1}] given by

$$K(h, x,z) = K_s(x,z)\, K_r(h,x,z) \qquad (3.15)$$

Where

K_r = the relative hydraulic conductivity [LT^{-1}],

K_s = the saturated hydraulic conductivity [LT^{-1}]

3.5.2 The unsaturated soil hydraulic properties

Equation 3.14 has nonlinear functions of pressure head for unsaturated soil hydraulic properties such as θ (h) and K(h). The model permits the use of three different analytical models for the hydaulic properties (Brooks and Corey, 1966; Van Genuchten, 1980; and Vogel and Cislerova, 1988). The model also implements the soil-hydraulic functions of Van Genuchten (1980), who used the statistical pore-size distribution model BY Mualem (1976) to obtain a predictive equation for the unsaturated hydraulic conductivity function in terms of soil water retention parameters.

Water content and hydraulic conductivity, which are illustrated in Figure 3.9, taken from hydraulic equations implemented in HYDRUS_2D are those by Vogel and Cislerova (1988) who modified the equations of Van Genuchten (1980) to add flexibility in the description of the hydraulic properties near saturation. As shown in Figure 3.9, while the change from θ_s to θ_m has little or no effect on the retention curve, the effect on the shape and value of the hydraulic conductivity function can be considerable, especially for fine-textured soils with parameter $\theta_a \leq \theta_r$.

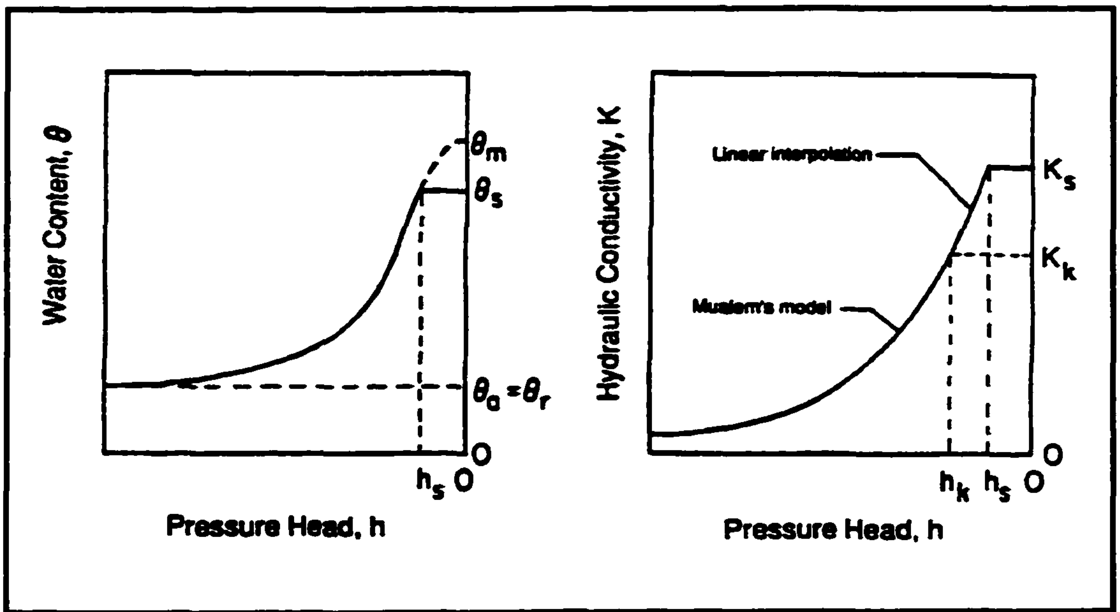

Figure 3.9. Schematics of the soil water retention(a) and hydraulic conductivity (b) respectively (Simunek et al. 1999).

To increase the flexibility of the analytical expression, the parameter θ_r in the retention function was replaced by the functions (extrapolated). The approach maintains the physical meaning of θ_r and θ_s as measurable quantities. The curve shows that the predicted hydraulic conductivity function is matched to a measured value of the hydraulic conductivity, $K_k = K(\theta_k)$, at some water content θ_k less than or equal to saturated water content, $\theta_k \leq \theta_s$ (Vogel and Cislerova, 1988).

3.5. 3 Solute transport

3. 5.3.1 Governing transport equation

In the governing transport equation, the partial differential equation governing two-dimensional chemical transport during transient water flow in a variably saturated rigid porous medium is taken as:

$$\frac{\partial \theta c}{\partial t}+\frac{\partial \rho s}{\partial t}=\frac{\partial}{\partial xi}\left(\theta D_{ij}\frac{\partial c}{\partial x_j}\right)-\frac{\partial q_i c}{\partial x_i}+u_w\theta c+u_s\rho s+\gamma_w\theta+\lambda_s\rho-Sc_s \tag{3.16}$$

where

c = the solution concentration [ML^{-3}],

s = the adsorbed concentration [-],

q_i = the i-th component of volumetric flux [LT^{-1}],

u_w and u_s = first-order rate constants for solutes in liquid and solid phases [T_{-1}], respectively; γ_w and λ_s = zero-order rate contents for solute in the liquid [$ML^{-3}T^{-1}$] and solid [T^{-1}] phases, respectively;

ρ = the soil bulk density [ML^{-3}],

S = the sink term in the water flow equation (1),

c_s = the concentration of the sink term [ML^{-3}], and

D_{ij} = the dispersion coefficient tensor [L^2T^{-1}]. The four zero—and first-order rate constants in (3.16) may be used to present a variety of reactions or transformations including biodegradation, volatilization, precipitation and radioactive decay.

HYDRUS_2D assumes equilibrium interactions between the solution (c) absorbed (s) concentrations of solute in the soil system. The absorption isotherm relation of s and c is described by a linear equation of the form:

$$s = kc \tag{3.17}$$

where

k = an empirical constant [LM^{-1}]

The following continuity equation describes isothermal Darcian flow in a variably saturated porous medium:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q_i}{\partial x_i} - S \tag{3.18}$$

Substituting equation (3.16) and (3.18) into (3.17) gives:

$$-\theta R\frac{\partial c}{\partial t} - q_i\frac{\partial c}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial c}{\partial x_j}\right) + Fc + G = 0 \tag{3.19}$$

where

$$F = u_w\theta + u_s\rho k + S \tag{3.20}$$

$$G = \gamma_w\theta + \gamma_s\rho - Sc_s \tag{3.21}$$

And where the retardation factor R [-] is defined as

$$R = 1 + \frac{\rho k}{6} \tag{3.22}$$

Where

γw = zero-order rate constants for solutes in liquid phase. [$ML^{-3}T^{-1}$]

γs = zero order rate constant for solutes absorbed onto the solid phase[MLT^{-1}]

ρ = bulk density of porous medium [M/L^3]

In order to solve equation (3.19), it is necessary to know the water content θ and the volumetric flux q_i. Both variables are obtained from solutions of the Richards equation.

3.5.4 Numerical solution of the solute transport equation

In this study, the soil profile was assumed to consist of one homogeneous layer. This assumption was made due to similar textures under field conditions. The hydraulic parameters of the Van Genuchten-Mualem model of test soils are listed in Table 3.5. The Galerkin finite element method is used to solve the solute transport equation (3.19) subject to appropriate initial and boundary conditions. The solution procedure largely parallels the approach used for the flow equation (for more details see Simunex et al.(1999)

Table 3.5. Parameter values of hydraulic properties of the field soil.

Soil	Ks (cm/day)	Θ_r	Θ_s	α	n
Clay soil	5.97	0.068	0.38	0.008	1.09

CHAPTER 4

RESULTS AND DISCUSSION

The results of this study are presented and discussed separately for the 1999 and 2000 growing seasons. The salt concentration results are discussed separately for each season because of the differences in treatments and sample design that were used in the two years. The adjustments to the 1999 treatments were done because of the insignificant results for the average salt concentration in the root zone between the treatments. Therefore, the aim of the change in experimental design in 2000 was to increase the variation between the treatments in order to produce significant differences.

4.1 1999 Field experiment

4.1.1 Effect of irrigation management on salt distribution in the root zone in 1999

The salt concentrations in the root zone for three depths during three periods of the irrigation season were averaged over blocks and resulted in Figures 4.1 to 4.7 and in Table A.1 in Appendix A. Statistically, there were no significant differences among treatments in the average of the electrical conductivity of soil samples. However, there were significant differences in EC in depths with the same treatments and between different treatment depths. The interactions of treatment by depths, and treatment by sample location produced significant differences in the salt concentration as presented in Table 4.1. Vertically, the results showed a significant difference between the EC of T1

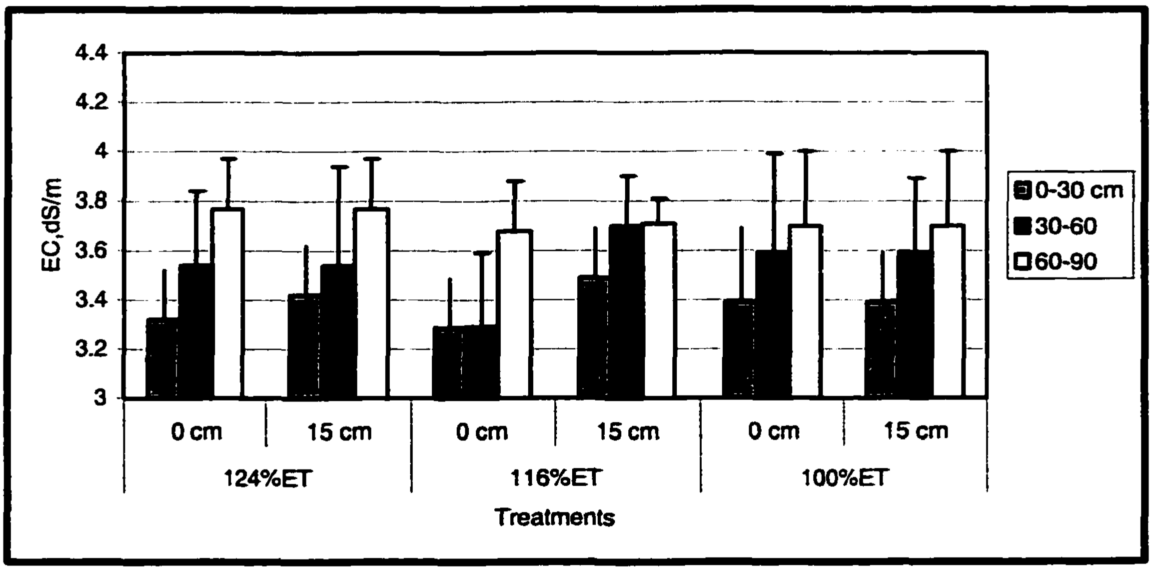

Figure 4.1. Initial salt distribution for the treatments irrigated every 7 days, 1999 season.

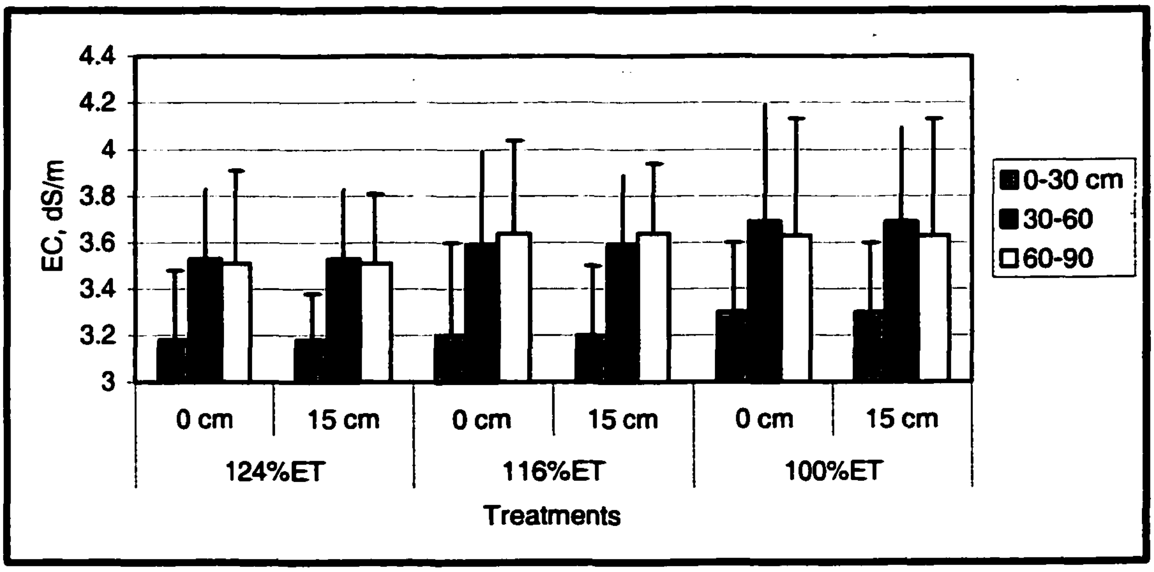

Figure 4.2. Initial salt distribution for the treatments irrigated every 3 days, 1999 season.

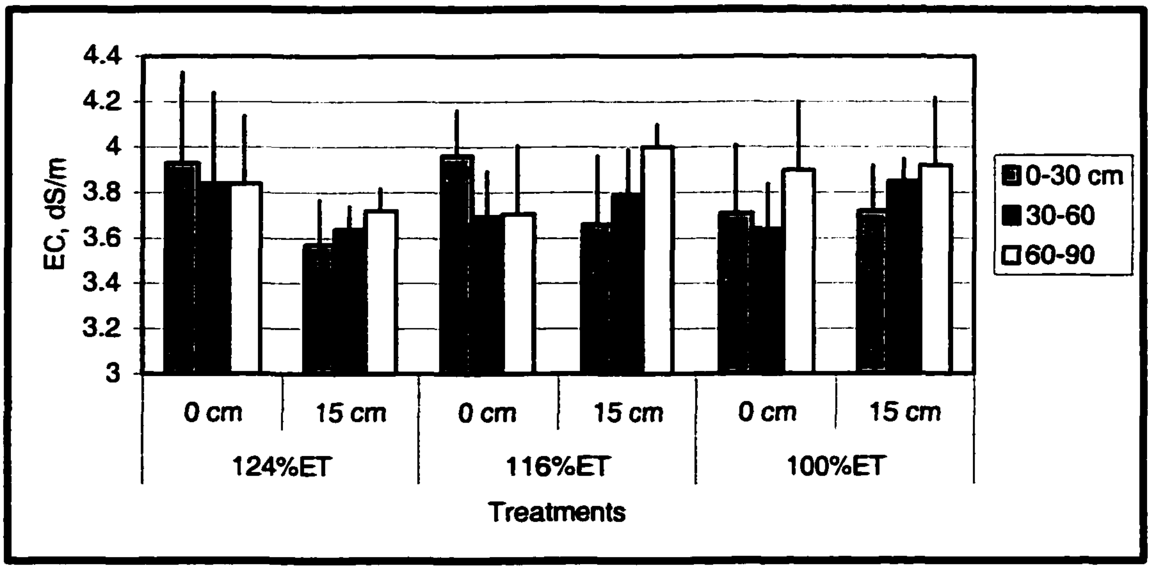

Figure 4.3. Salt distribution at the mid-season for the treatments irrigated every 7 days, 1999 season.

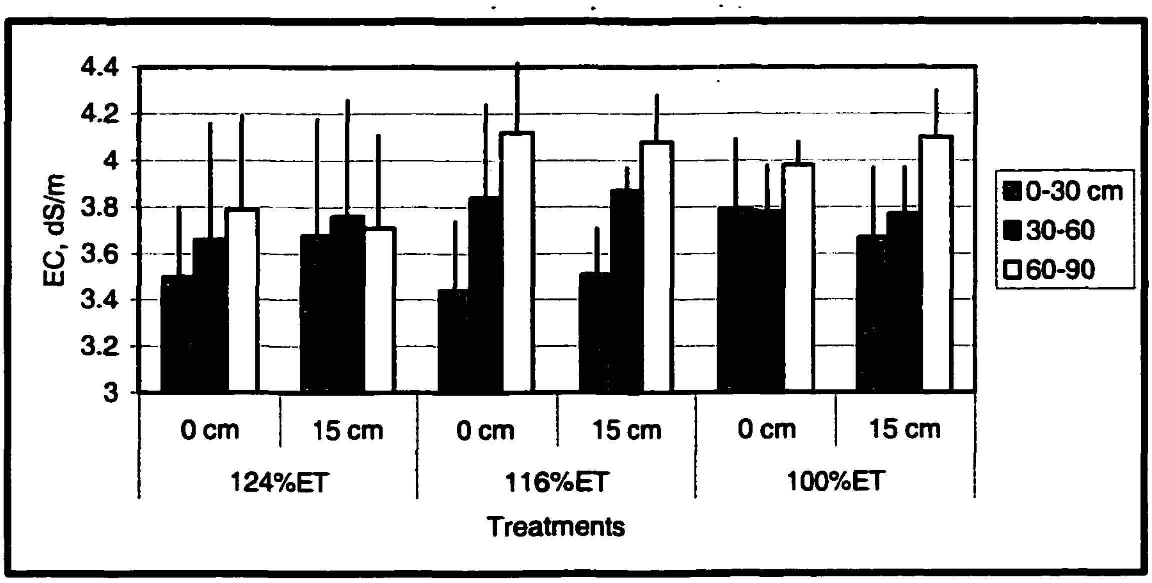

Figure 4.4. Salt distribution at the mid-season for the treatments irrigated every 3 days, 1999 season.

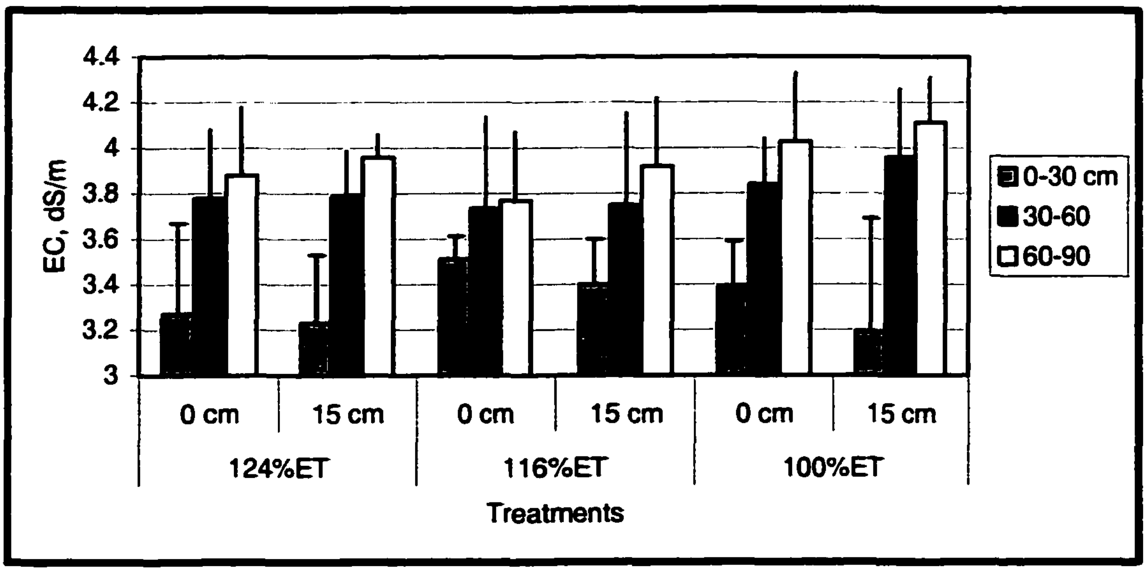

Figure 4.5. Salt distribution at the end of 1999 season for the treatments irrigated every 7 days.

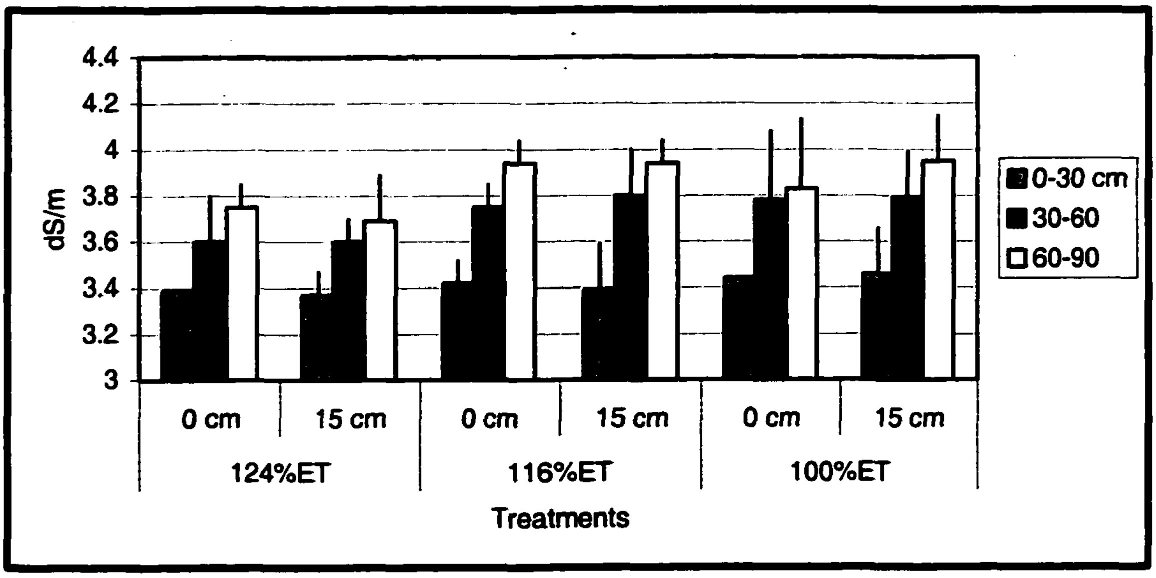

Figure 4.6. Salt distribution at the end of 1999 season for the treatments irrigated every 3 days.

compared with T5 and T6 at the depth of 60-90 cm (at alpha 0.05). Furthermore, there were significant differences between the following depths of each treatment: the EC of T2 at depths 0-30 cm and 60-90 cm, T3 at depths 0-30 cm and T3, T5 at depths 0-30 cm and 30-60 cm, T5 at depths 0-30 cm and 60-90 cm, T5 at depth 30-60 cm and 60-90 cm, T6 at depths 0-30 cm and 60-90 cm, and the EC of T6 at depths 30-60 cm and 60-90 cm. In the horizontal direction, the salt concentration was significantly different in some treatments (T1 and T6) between 0 cm and midway between the emitters (15 cm).

Table 4.1. Type 3 Tests of EC Fixed Effects, for factorial experiment, 1999.

Effect	Num*, DF	Den*, DF	F value	Pr> F	Remarks*
Treat.	5	15	0.29	0.9123	Not Sig.
Depth	2	6	9.15	0.0151	Very Sig.
Treat*depth	10	80	3.22	0.0016	Very Sig.
Location of sample	1	3	0.05	0.8453	Not Sig.
Treat*location of sample	5	80	2.80	0.0220	Sig.
Depth*location of sample	2	80	0.55	0.5789	Non Sig.
Treat*depth*location of sample	10	80	0.95	0.4930	Non Sig.
EC1	1	80	6.91	0.0103	Sig.

*(Sig.) significant.
*Num= numerator
*Den= denominator
Treat.= treatment

The insignificant differences in salt concentration among the treatments are probably related to three reasons: the rainfall during the season which pushed the accumulated salts from the top of the soil to the lower layers (60-90 cm). As is shown above, uniform salt distribution occurred near the surface with distance along the lateral. No patterns reflect salt accumulation midway between emitters. This is probably related to the small spaces between the emitters, plants that could create the uniformity of the water content in that small portion of the soil, and the short growing season. Maximum soil salinity accumulation occurred in all treatments at the 60-90 cm depth, especially at the end of the season. This may be due to the leaching effect of salts by irrigation water and precipitation.

Although the amount of irrigation water that was added with each treatment and the interval between irrigations were different, the concentration of soil salinity in the root zone occurred maximally at the 60-90 cm depth. This unexpected result of salt concentration is probably due to the rainfall conditions during the growing season. The rainfall drained the salt concentrations downward to the 60-90 cm depth for all treatments. During the growing season, rainfall occurred immediately after the irrigation event in some cases, which increases the chance to leach the salts toward the bottom of the root zone. Because of this, there was an insignificant difference in salt accumulation among the 1999 treatments. Trends showed the lowest salt accumulation in the root zone with 124%ET and three days interval irrigation interval (T4) compared to other treatments. However, the highest average concentration occurred for the 100% ET irrigation treatment for both the seven (T3) and three day (T6) irrigation intervals as is shown in Figure 4.7 as expected. The results of salt accumulation under trickle irrigation in this study were different with depth than those recovered by Pasternake et al. (1995). Pasternake et al. (1995) found that the concentration of salt, from highest to lowest, was at depths 0-30, 30-60, and 60-90 cm, respectively.

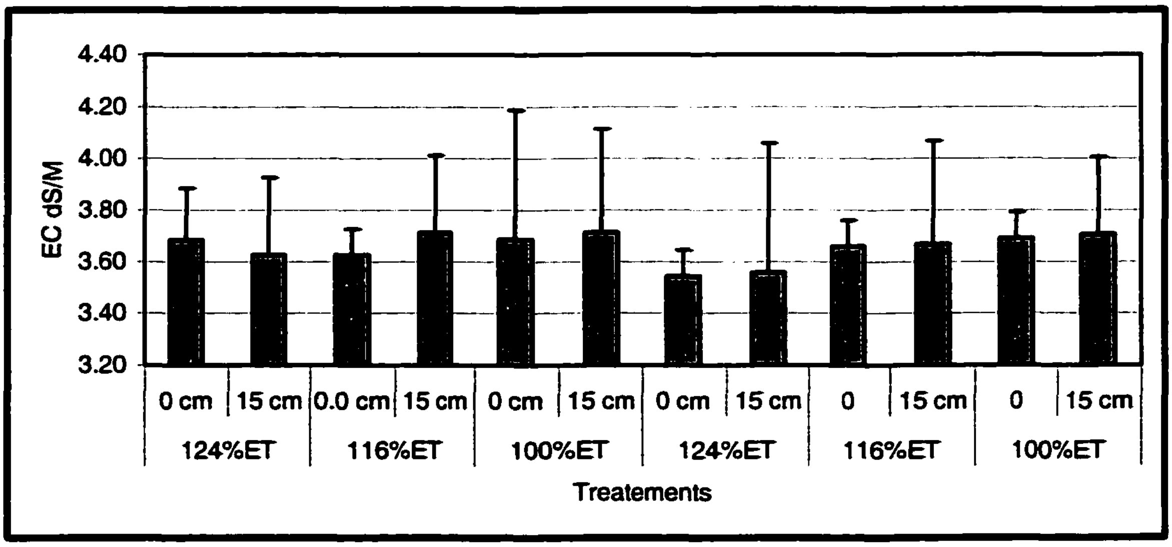

Figure 4.7. Total average salt concentration of 1999 field treatments.

In Hanson and Bendixen (1995), the results showed that the soil salinity near the drip tape was less than the salinity of the irrigation water. That may due to the dilution effect, whereby the salinity of the extract can be less than the salinity of the irrigation water under high frequency irrigation if the soil sample is taken close to the water source.

In this study, in the 1999 cropping season, the result was the opposite of Hanson and Bendixen (1995). The result showed that soil salinity near the drip tape was higher than the irrigation water. The reasons for this result may be due to rainfall, which caused leaching of the accumulated salt on the top of the soil surface around the drip tape and pushed it beneath the emitter. From this result, there is some concern that small amounts of rainfall during the cropping season may move the accumulated surface salts into the part of the root zone with high root density. This highly saline soil water could affect crop growth. However, little information is available on this potential effect. So, to avoid this effect, operating the drip system during rainfall in an attempt to dilute the highly saline surface soil water and push salt out of the root zone, might be reasonable.

4.1.2 Crop production and water use efficiency

The total fresh ears were collected for each plot and were classified as marketable and non-marketable visually, and then marketable ears were weighed. The influence of irrigation treatment on average crop root zone salinity at the end of the season, water use efficiency, and fresh ear yield were investigated (Table 4.2). Increasing the amounts of irrigation water to 124%ET slightly decreased the salt concentration in the root zone; however, the factor that increased crop production the most was the shorter irrigation interval of 3 days compared to 7 days. Statistically, there were significant differences between the total average weight of fresh ear yield as presented in Table 4.2. Amount of irrigation water did not impact yield; however, the highest yield occurred for the 116%ET treatment for both 3 and 7 day intervals compared to the other treatments. This might be due to the high amount of water which leached the fertilizer out of the root zone under 124%ET treatment. However, the non-leached 100%ET treatment may be caused stress by reducing the availability of water in the crop root zone. Yield reductions were 10%, 7%, and 10% under T1, T2, and T3, respectively for the 7 day irrigation interval, and 5%, 4%, and 7% under T4, T5, and T6 for the 3 day irrigation interval, although the average values of the accumulated salt in the active root zone were reported as 3.3, and 3.77 dS/m for the previous irrigation intervals respectively. Golberg et al. (1971) concluded that no reduction occurred in sweet corn yield as irrigation water increased from 1.0 to 3.0 dS/m. This result was obtained probably because the experiment was conducted in coarse-textured soil that had a low of initial salt concentration (0.5-1.0 dS/m) and because soil salinity was than salinity of in the irrigation water.

Table 4.2. Average sweet corn yield as influenced by salinity, amount of irrigation water, irrigation frequency, and water use efficiency (WUE), 1999.

Treatments	Rain. (mm)	Total amount (mm)	Irr. Inter. (days)	Salinity (dS/m)	Fresh ears (Ton/ha)	WUE (Kg/M^3)	S.E	RY %	S.E
T1 (124%)	78	359	7	3.66	22.7 a*	6.3	0.01	90	2.0
T2 (116%)	78	338	7	3.67	23.5b*	6.9	0.04	93	1.4
T3 (100%)	78	296	7	3.70	22.8a*	7.7	0.01	90	1.0
T4 (124%)	78	359	3	3.56	24.1b*	6.7	0.03	95	3.8
T5 (116%)	78	338	3	3.67	24.3b*	7.2	0.05	96	1.8
T6 (100%)	78	296	3	3.70	23.7b*	8.0	0.03	93	3.5

*Values with same letters are insignificant.
S.E = Standard error (was taken for all average WUE, RY, and salt distribution)
RY= Relative yield

On the other hand, Mass and Hoffman (1977) reported that a 2.5 dS/m irrigation water salinity resulted in a 25% sweet corn yield reduction. Abu Awwad (1995) indicated an 8% yield reduction in sweet corn at 3.6 dS/m. So, crop responses to irrigation water salinity will vary depending upon climate, irrigation water salinity, soil conditions, irrigation method, corn variety, and cultural and irrigation management.

The relative crop water production function of total un-husked ears vs. relative water applied for the 1999 growing season, shown in Figure 4.8, indicates the maximum yield under 116%ET for the 3 day interval between irrigations. Figure 4.8, indicates the ranking of relative yield, highest to lowest, at 116%, 124%, and 100% ET for the 3 day irrigation interval. For treatments irrigated after seven days, the ranking of yields, highest to lowest was 116%, 124, and 100% ET respectively. The water use efficiency shown in Figure 4.9, indicates the ranking from highest to lowest at 100%, 116%, 124%ET for the 3 day irrigation interval. For treatments irrigated after 7 day, the ranking of yields, highest to lowest was 100%, 116%, and 124%ET respectively. This is probably related to the high water holding capacity of clay soil being to show an irrigation response to the small differences in the irrigation water. However, deficit irrigation water might produce water stress and reduced crop yield, and more irrigation water than required for leaching could cause deep percolation of chemicals, including fertilizer. The result indicated that some deep percolation might have occurred with maximum irrigation quantities, indicating that deficit (100%ET) irrigation can achieve near-maximum yields with substantial water savings. The optimum level for irrigation depends, of course, on the price of irrigation water and sweet corn, irrigation and fertilization methods, and soil texture.

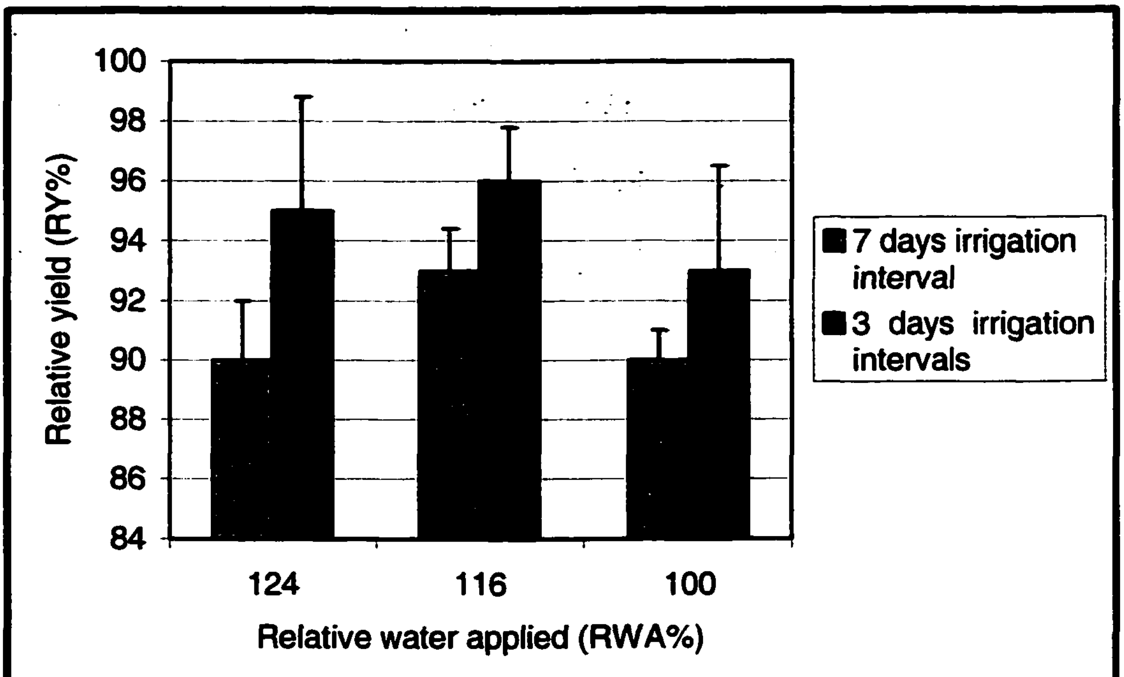

Figure 4.8. Relative sweet corn as a function of relative water applied yield, 1999 season

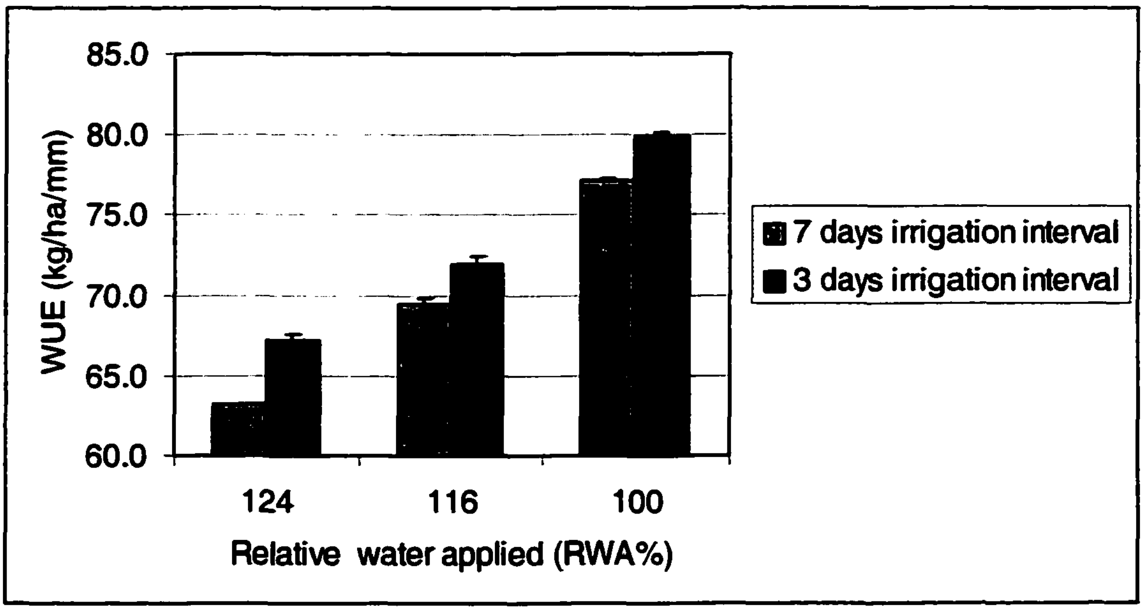

Figure 4.9. Water use efficiency (WUE) on un-husked fresh ear yield per unit water applied, a function of ET, 1999 season.

4.2 2000 Field experiment

4.2.1 Effect of irrigation management on salt distribution in the root zone in 2000

The influence of irrigation treatment on average crop root zone salinity during three stages of the growing season presented a significant difference among the treatments of the 2000 experiment. Table 4.3 presents the type 3 tests of fixed effects and shows significant differences in EC for depth and location.

Additionally, the interactions of depth by location of sample also showed significant differences. However, the interactions of treatment by location and treatments by depth by location of sample did not show significant effects of salt concentration in the crop root zone. As shown in Table A.2, Appendix A, the average salt distribution varied according to the amount of irrigation water, irrigation frequency, and the initial salinity of the field soil and irrigation water. The experiment started with slightly higher initial

Table 4.3. Type 3 Tests of EC Fixed Effects, for factorial experiment, 2000.

Effect	Num DF	Den DF	F Value	Pr> |t|	Remarks*
Treat.	5	15	3.60	0.0244	Sig.
Depth	5	15	3.02	0.0440	Sig.
Treat*Depth	25	179	1.20	0.2486	Not Sig.
Location of sample	1	3	9.50	0.0540	Sig.
Treat*Location of sample	5	179	0.65	0.6604	Not Sig.
Depth*Location of sample	5	179	7.45	0.0001	Very Sig
Treat*Depth*Location of sample	25	179	0.67	0.8851	Not Sig.
EC1	1	179	3.89	0.0502	Sig.

* Sig. = significant difference

salinity in the root zone compared to the 1999 season. The initial salt concentration in the soil was 4.65, 4.96, 5.24, 5.49, 5.64, 5.41 dS/m at 0-15, 15-30, 30-45, 45-60, and 60-75, and 75 –90 cm depths, respectively (Figure 4.10 and 4.11). Using saline irrigation water with different leaching frictions resulted in a significant increase in the average crop root zone salinity during the growing season as shown in Figure 4.10 to Figure 4.15 and Table A.2, in Appendix A. Decreasing the amount of applied irrigation water increased the salt concentration in the root zone. The highest accumulation occurred for the 100%ET treatment. Average root zone salinity decreased as the amount of applied irrigation water increased over the seasonal crop water use because some of the accumulated salts leached. Using saline water with deficit irrigation (100%ET) could be a serious problem if there is not enough water to leach the accumulated salts from the vicinity of the crop root zone. With excess irrigation (115% and 130% ET), average crop root zone salinity might be managed to maintain salt accumulation at a minimum. Tscheschke et al. (1974) indicated the highest salt concentration and the lowest soil water potential occurred, in general, for irrigated conditions compared to non-irrigated. With deficit irrigation

(100%ET) salts tended to accumulate close to emission points, which aggravates the problem. However, for higher irrigation amounts (115% and 130% ET), salts tended to accumulate close to the soil surface midway between the laterals. As the horizontal distance from the drip tape increased, less leaching occurred, and consequently, high salinity accumulation occurred near the edge of the bed. In the vertical direction, the highest concentration of the salt occurred at the 30-60 cm depth under both the 100 and 115%ET treatments in the mid-season. However, the 130%ET treatment showed lower salt concentration and more salt distribution uniformity (small marge different of salt concentration for different depths) in the root zone due to the large amount of leaching. In the 115%ET and 7 day interval treatment, the highest salt concentration was 5.17 dS/m at the 45-60 cm depth. For the treatment an EC of 100%ET 5.5 dS/m the highest salt accumulation occurred at the 15-30 cm depth. The salinity patterns show that no leaching of salt occurred throughout the profile for the deficit treatment. On the other hand, the salt concentration was 5.1 dS/m at the 60-75 cm depth under the 115%ET treatment, and 5.87 dS/m at the 0.0–30 cm depth under the 100%ET treatment for the 2 day irrigation interval. The salinity levels may reflect the downward movement and dispersion of the near surface salts due to multiple rainfall events.

In fact, soil water availability and depletion were reduced as irrigation water and soil salinity increased probably due to an increase of osmotic pressure that was caused by the salt concentration in the root zone. Increasing irrigation frequency could reduce the effect of osmotic pressure in the root zone. Under these conditions, soil water content increased, but soil water availability decreased as irrigation water salinity increased. As shown in the results, the higher the leaching fraction, the lower the salinity of the soil in the vicinity of the emitters. Patterns of soil water content, as described by soil matric potential, were determined in the 7 day interval for treatments that have very small leaching fraction (100%ET). Increasing the frequency of irrigation significantly decreased the negative effect of salinity in crop production, which was reflected by the crop production. The positive effects of applying irrigation water more frequently to plants growing in saline environments were stated by Mass and Hoffman (1977). The higher the matric potential, the higher the soil water content. The management of irrigation under the above conditions is very complicated and needs to be quantified carefully to avoid unexpected crop and soil damage as a result of using random irrigation management. The most practical solution to reduce the effects of salinity conditions is increasing irrigation frequency and increasing the amount of water to remove the salt from the root zone. For more details of salt distribution during three stages of the growing season see Table A.2, in Appendix A.

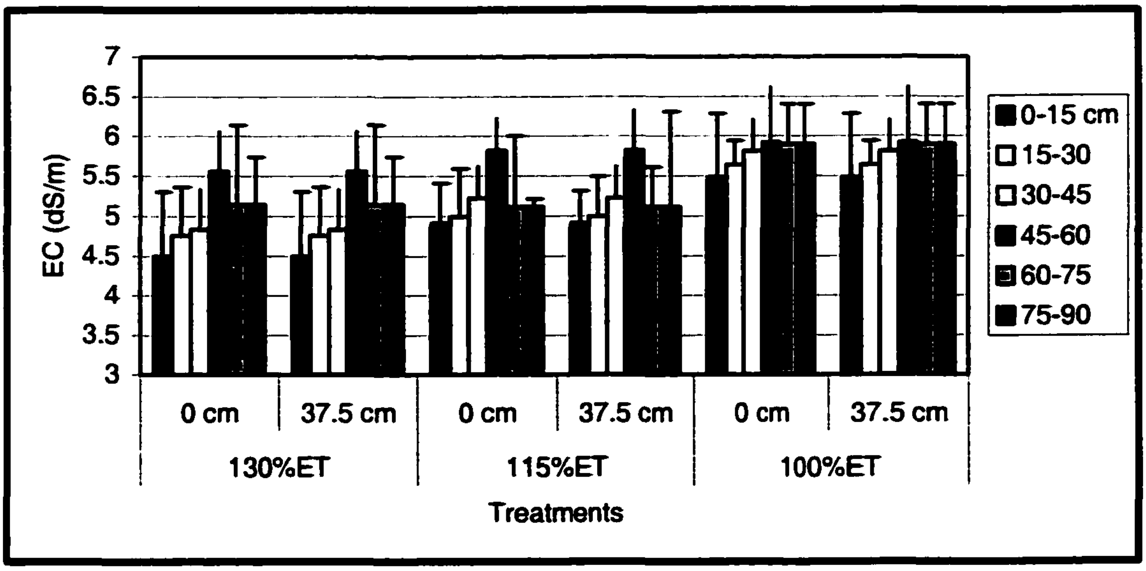

Figure 4.10. Initial salt distribution for the treatments irrigated every 7 days (2000 season).

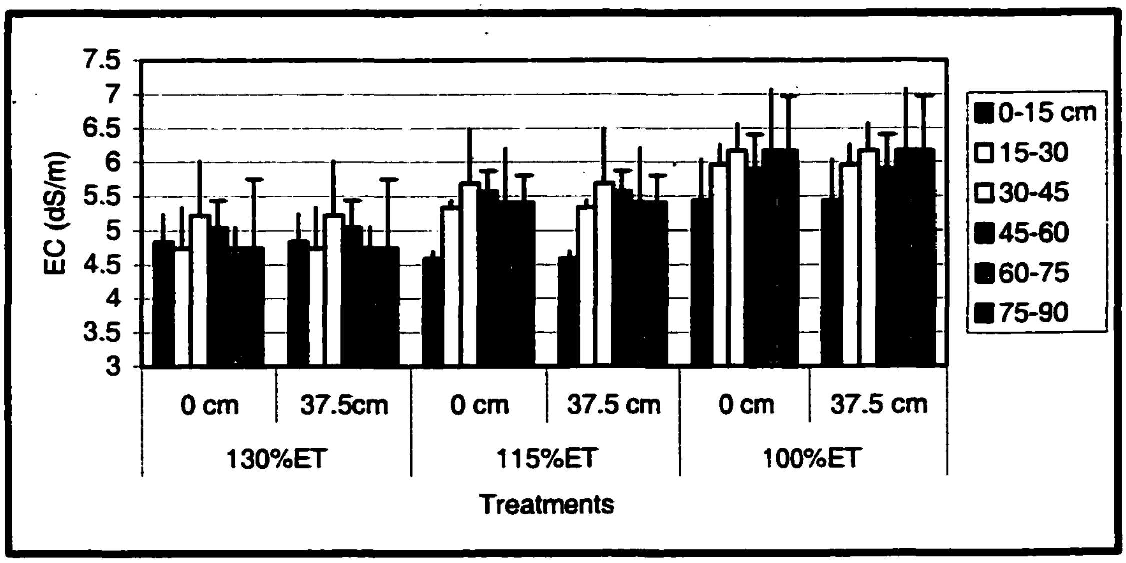

Figure 4.11. Initial salt distribution for the treatments irrigated every 2 days (2000 season).

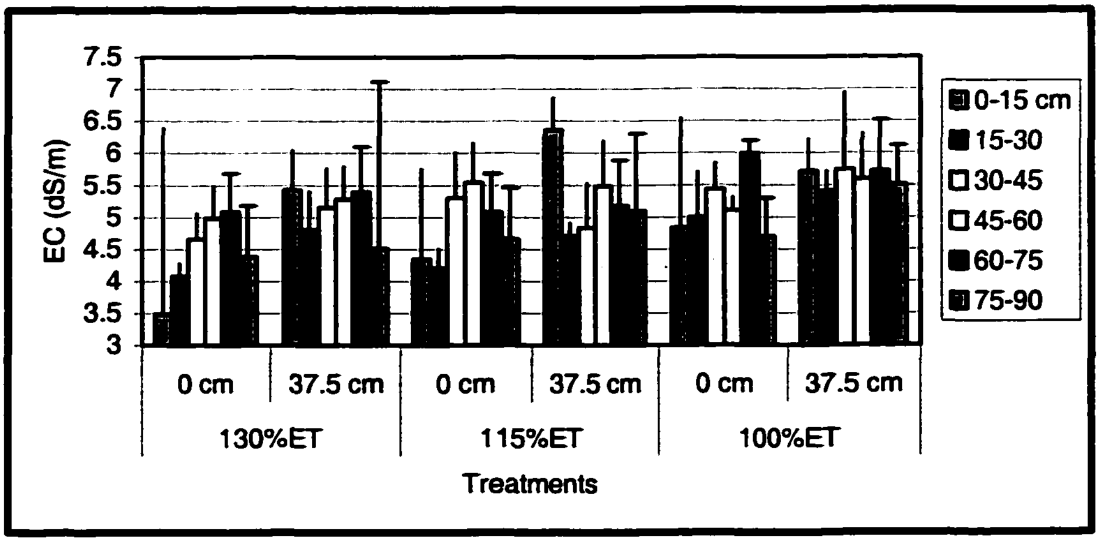

Figure 4.12. Salt distribution for the treatments irrigated every 7 days, mid-season, 2000.

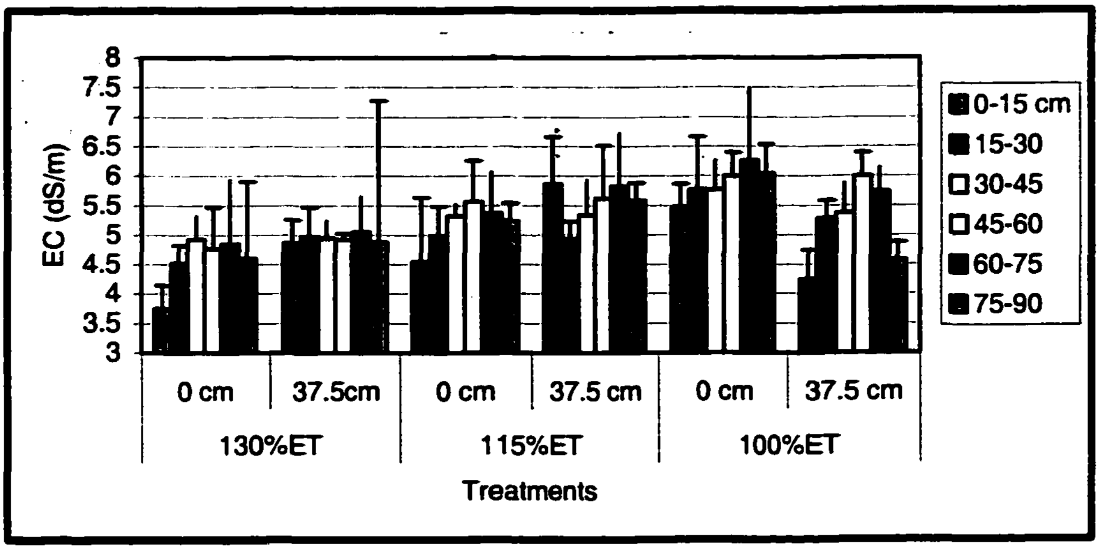

Figure 4.13. Salt distribution for the treatments irrigated every 2 days, mid-season, 2000.

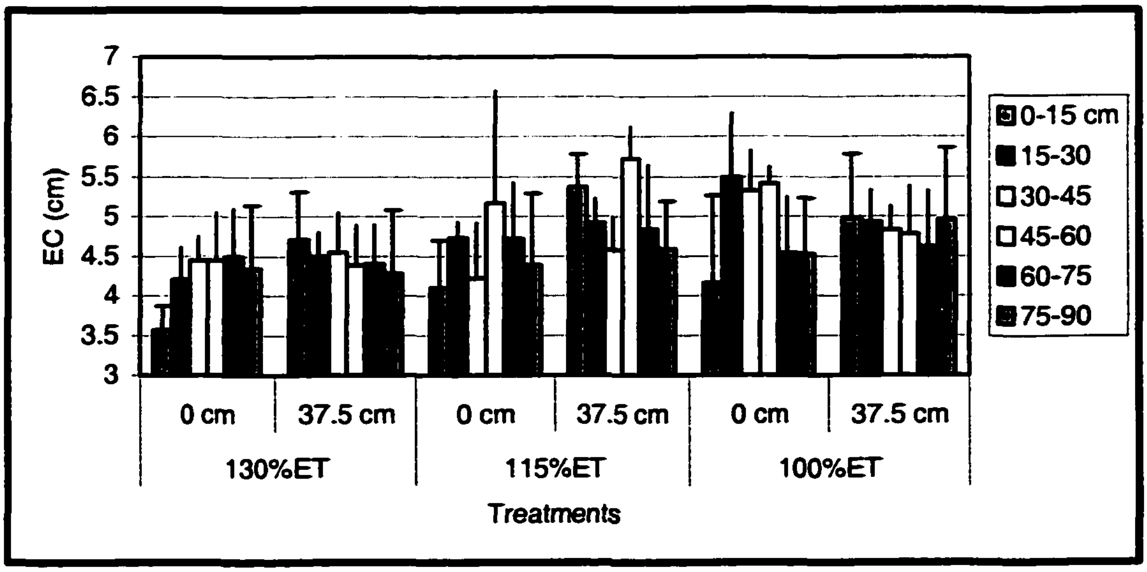

Figure 4.14. Salt distribution for the treatments irrigated every 7 days, end of 2000 season.

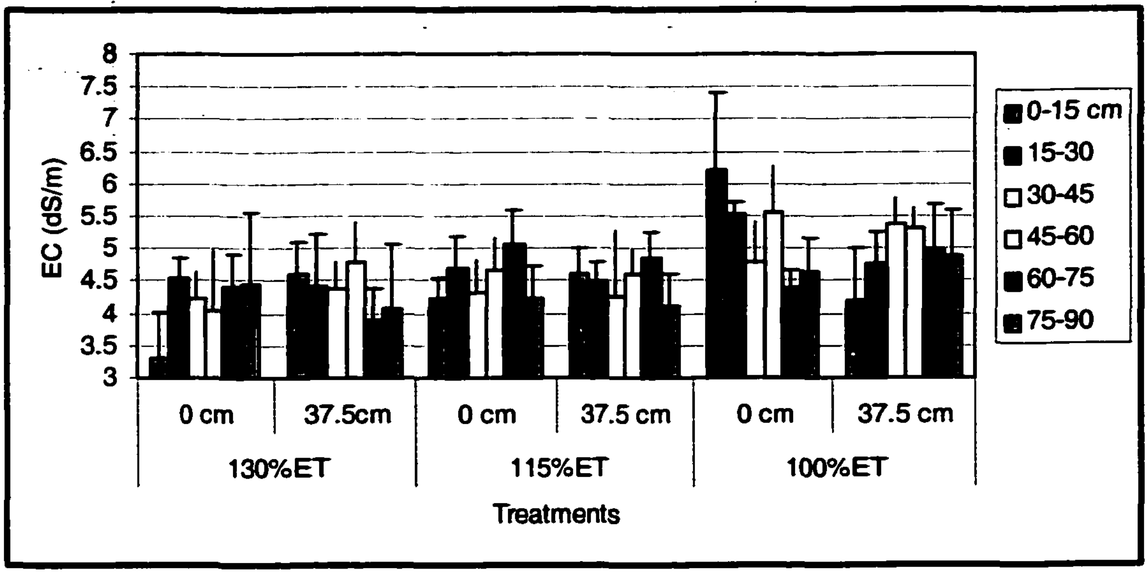

Figure 4.15. Salt distribution for the treatments irrigated every 2 days, end of 2000 season.

4.2.2 Crop production and water use efficiency

The total fresh ears were collected at an optimum maturity from the middle of the treatment to avoid the affects of the boundary conditions in the results of the sweet corn fresh ears. In the 2000 season, there were additional procedures done to emphasize and reflect the real production. The fresh ears were harvested on September 19, 2000 and the crop was classified in commercially as marketable. The production was specified in two ways, by total marketable weight, and graded as fancy, U.S. No.1, and U.S. No.2 according to the as U.S standard of fresh ears of sweet corn as is shown in Table 4.4. The total amount of seasonal irrigation water, including rainfall was 372, 333, and 294 mm for 130%ET, 115%ET, and 100%ET treatments, respectively, for both irrigation intervals: 2 and 7 days. As the results show in Table 4.4, the highest percentage of fancy (>15.2 cm) was obtained under the highest amount of irrigation

Table 4.4. Total an average sweet corn weight and U.S grades No. (2000 season)

Treatments	Total water (mm)	Total mass (Ton/ha)	Fancy (>15.2 cm)	U.S.No.1 (10.2-15.2cm)	U.S. No.2 (<10.2 cm)
			%		
T1	372	21.8b*	51	31	18
T2	333	24.5a*	48	31	21
T3	294	23.2a*	43	37	20
T4	372	25.0a*	62	19	19
T5	333	26.3a*	50	33	17
T6	294	23.9a*	44	37	19

*The same letters means insignificant.

water with 2 interval days between irrigations. In the 7 day interval, the highest total yield was obtained under the 115%ET treatment. This was the same result for both irrigation frequencies.

Generally, the highest fresh ear yield was obtained under high irrigation frequency in this experiment. This result might reflect the crop's response to the soil water content and the osmotic potential for different irrigation water amounts and irrigation frequencies. Also, the results reflected the response of crop production to chemicals leached from the root zone under different amounts of irrigation water that drained throughout the root zone. The critical point in these results could be the balance between the salt leaching and the fertilizer retention in the root zone.

Water use efficiency (WUE) for un-husked ears vs depth of irrigation water is illustrated in Figure 4.16. The results indicate that the highest WUE was obtained under the highest irrigation frequency in the 2000 growing season. On the other hand, the deficit irrigation treatment (100%ET) showed the highest values of WUE in both irrigation frequencies. The results showed the highest crop production was obtained under 115%ET for both irrigation frequencies. The results indicated the most important factor in WUE and relative yield was irrigation frequency. This may be due to the uniform water content in the root zone during the growing season, especially under clay soil conditions, since clay has the ability to retain the water and fertilizer in the soil versus evapotranspiration and deep percolation. The evaluation of WUE and relative un-husked ear yield allows one to better understand the alternative options of irrigation management under different conditions. The alternatives are leaching the salt out of the

Table 4.5. Average of sweet corn yield as influenced by salinity, amount of irrigation water, irrigation frequency, water use efficiency (WUE) and RY, 2000.

Treatments (ET)	Rain. (mm)	Total amount (mm)	Irr. Inter. (days)	Salinity (dS/m)	Fresh ears Ton/ha	WUE (Kg/M^3)	S.E	RY %	S.E
T1 (130%)	34	372	7	4.7	21.8a*	5.9	0.00	86	0.8
T2 (115%)	34	333	7	5.0	24.5b*	7.4	0.03	97	3.9
T3 (100%)	34	294	7	5.3	23.2a*	7.9	0.13	92	12.9
T4 (130%)	34	372	2	46	25.0b*	6.7	0.05	99	8.2
T5 (115%)	34	333	2	5.0	26.3b*	7.9	0.06	104	7.4
T6 (100%)	34	294	2	5.5	25.1b*	8.6	0.04	95	4.5

*Values with same letters are insignificant.
RY= Relative yield
S.E. Standard error

root zone, producing the highest production without concern for amounts of irrigation water, or saving irrigation water under scarce water resources. This result might help the irrigators and engineers build their management strategy based on their goals and local conditions.

Generally, in both the 1999 and 2000 field experiments, the results showed significant differences in salt concentration between the treatments and uniformity of salt distribution in the active root zone under the greatest amount of irrigated water treatment. However, the results presented were non-significant in the total average salt concentration among the treatments in the 1999 field experiment. On the other side, there was a significant difference in the average salt concentration in the root zone of the 2000 treatments. In both seasons, the results probably were affected by three factors: irrigation frequency, amount of irrigation water, and rainfall, as discussed in the previous sections. In both the 1999 and 2000 field experiment results, the deficit treatment (100%ET) produced the highest values of water use efficiency compared with other treatments.

In addition, the greatest fresh ear yield was obtained under the highest irrigation frequencies in both seasons. Also, total un-husked ear relative yield indicated the greatest values of yield under the 116%ET and 115%ET in the 1999 and 2000 seasons, respectively. The results were compared with Mass and Hoffman (1977) and Ayers and Westcott (1985) models. Due to the field conditions, the average relative crop yields were 79.3% for Mass and Hoffman (1977) model and 82% for the Ayers and Westcott (1985) model. All treatments produced relative yield more than the above model due to qualifying of trickle irrigation management under saline conditions. However, some treatments (115%ET) produced more than 100% of relative crop production compared to the control treatment irrigated by city water by the furrow irrigation system under local field practices. This result demonstrated the power and promise of using the trickle irrigation system under optimum irrigation management conditions for sweet corn in order to increase the crop production under saline condition in northern Colorado.

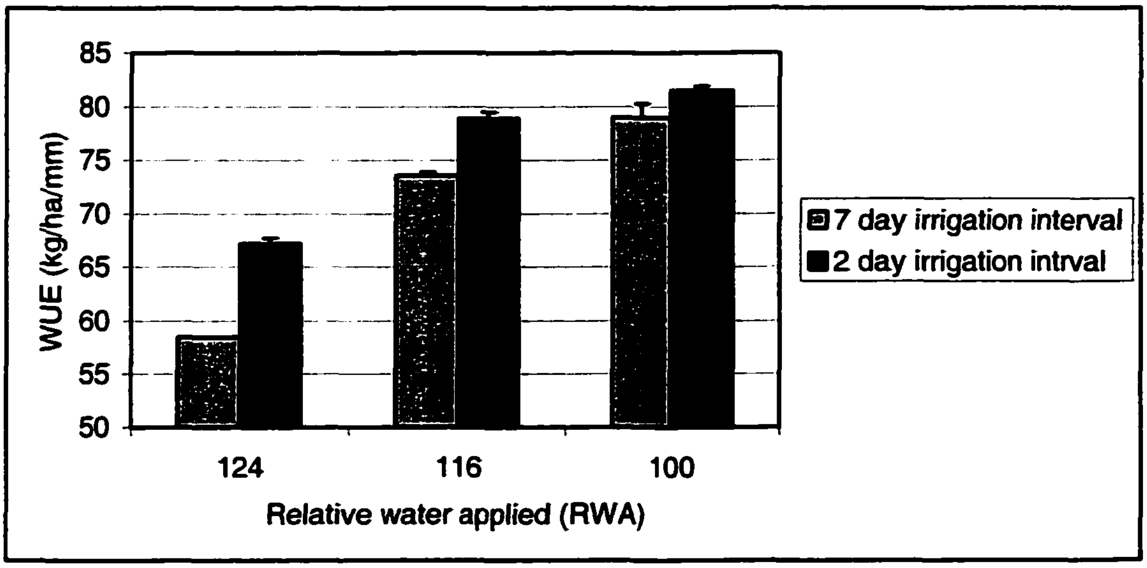

Figure 4.16. Water use efficiency (WUE) on un-husked fresh ear yield per unit water applied, as a function of ET, 2000.

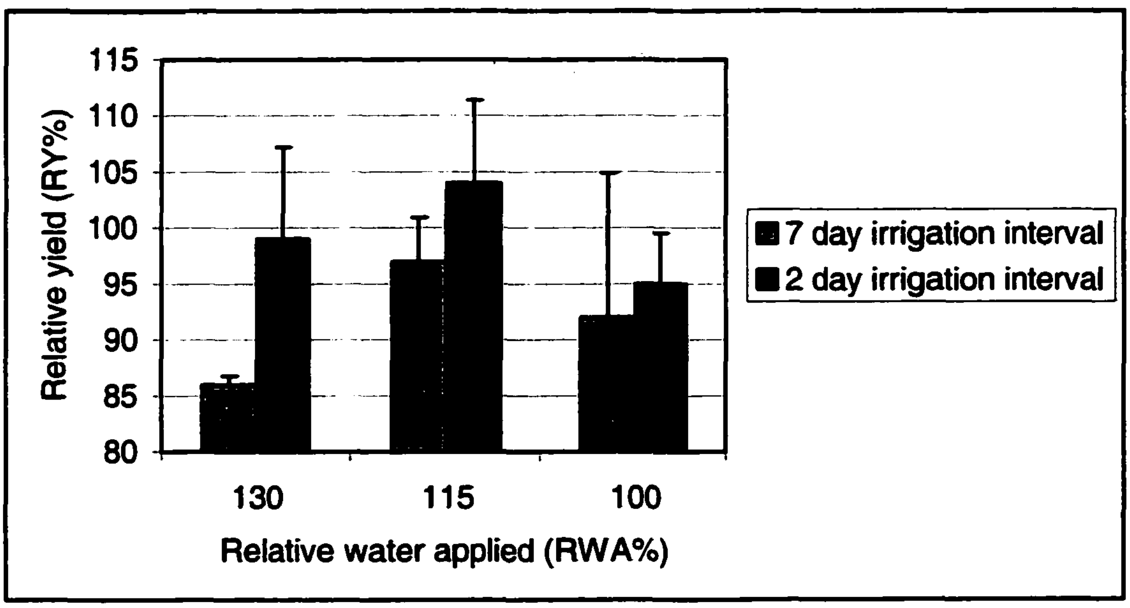

Figure 4.17. Relative total un-husked fresh ear yield, 2000.

4.3 Modeling (HYDRUS-2D) effort

A fundamental objective of the use of this model in this study is to compare the calculations to the data obtained from the field investigation. Once validated in this way, the model can be used to make decisions about irrigation system management. Salt concentration of the crop root zone can change depending on the soil and irrigation water salinity. In trickle irrigation, the solute movement distribution is complicated because the solute moves in two and three dimensions, affected by the amount of irrigation water, irrigation frequency, climatic and soil conditions. This complexity requires simulation models which can predict the concentration of salt in the active crop root zone in the vertical and horizontal directions. HYDRUS-2D will be emphasized to comparing the simulated data with the observation data to estimate sweet corn irrigation strategy management in the future based on the amount and irrigation frequency, root water uptake, and climate and soil conditions. The model uses a test statistic to compare measured data against simulated results. The model performance is judged perfect when there is no difference between observed and simulated data. The measured, saturated hydraulic conductivity for the experimental field, the initial salt concentration of soil and irrigation water, potential evapotranspiration, amount of irrigation water and irrigation frequency, and the amount of rainfall were used as input data for the two irrigation seasons to evaluate model performance.

In this study, RE values of 10% or less will be considered as good performance. However, RE greater than 10% will be evaluated as poor performance. Furthermore, by the index of agreement statistic (d) (Willmott, 1982), comparisons having values of 90, 80-90, and 70-80% will be considered as great, good, and acceptable performance, respectively. On the other hand, values less than 70% will be considered as poor performance of the model.

4.3.1 1999 growing season

4.3.1.1 Simulated prediction of salt distribution.

Table A.3 and Table A.4, in Appendix A show an average of the simulated data of salt concentration in the profile that was computed by the model at the end of the 1999 season in the active sweet corn root zone for each treatment midway between the emitters and at different depths under the emitters.

The model predictions of the average EC for each treatment are in the vertical and horizontal directions at different levels, shown in Figures 4.18, and 4.19, respectively. The results predict that the highest accumulated salt would be concentrated at a depth of 30-60 cm under the emitters and midway between the emitters. And, the lowest value of accumulated salt was predicted at a depth of 0-30 cm. The simulated result did not show that the salt accumulated in the top of the soil surface midway between the emitters as expected, probably due to the rainfall during the irrigation season and the small space between the emitters and corn plants, which caused leaching of the accumulated salt to a depth of 30-60 cm. The most important factor on the average accumulated salt in the active crop root zone was the amount of irrigation water that passed throughout the profile, which pushed the salts downward. Under the 124%ET treatments, there was the lowest average accumulated salt in the crop root zone. The highest salt accumulation was found under the 116%ET treatment for both irrigation frequencies as shown in Figures 4.20 and 4.21.

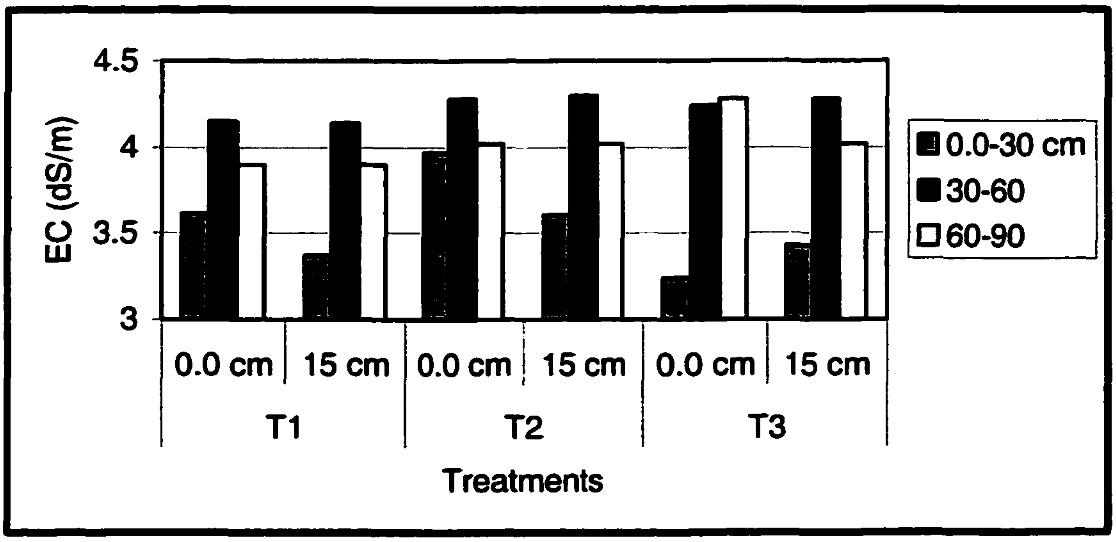

Figure 4.18. Simulated salt accumulation at different points in the root zone vertically and horizontally, 7 day irrigation interval treatments, 1999 season.

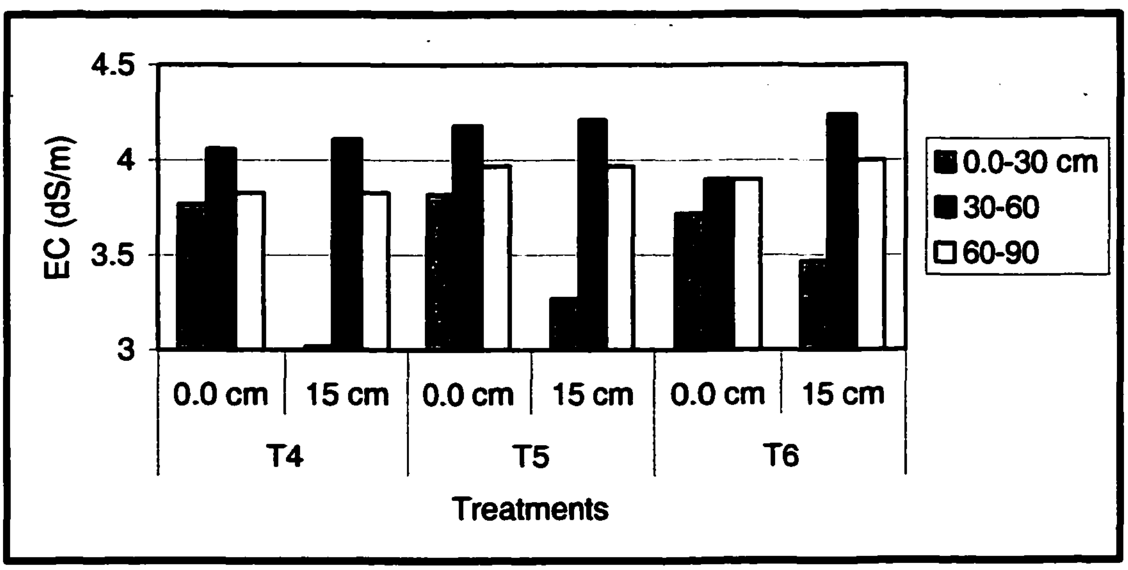

Figure 4.19. Simulated salt accumulation at different points in the root zone vertically and horizontally, 3 day irrigation interval treatment, 1999 season.

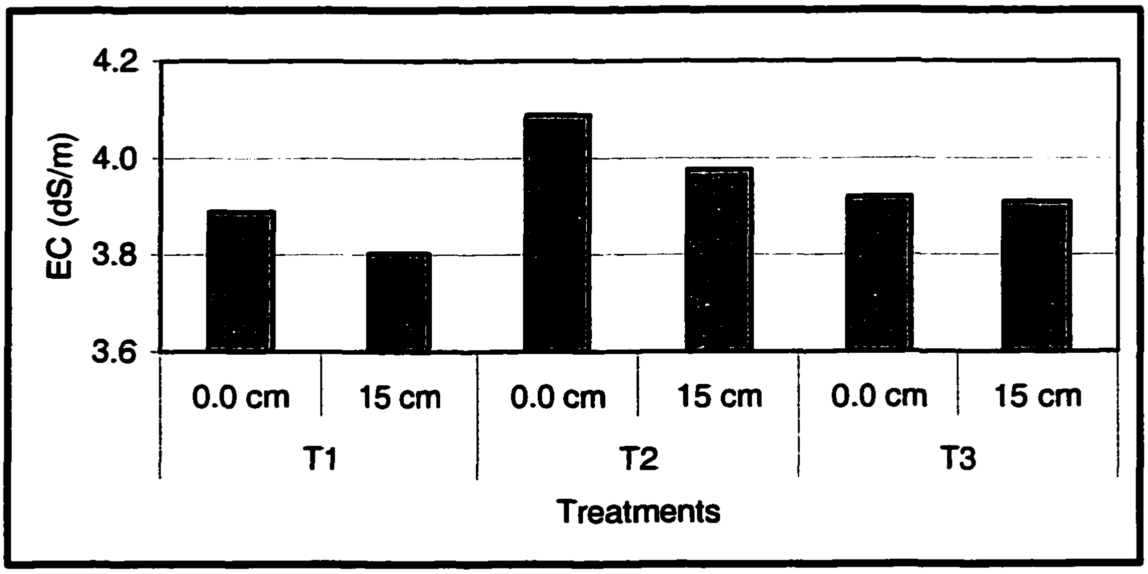

Figure 4.20. Predicted average accumulated salt in the root zone for the 7 day irrigation interval treatments, 1999 season.

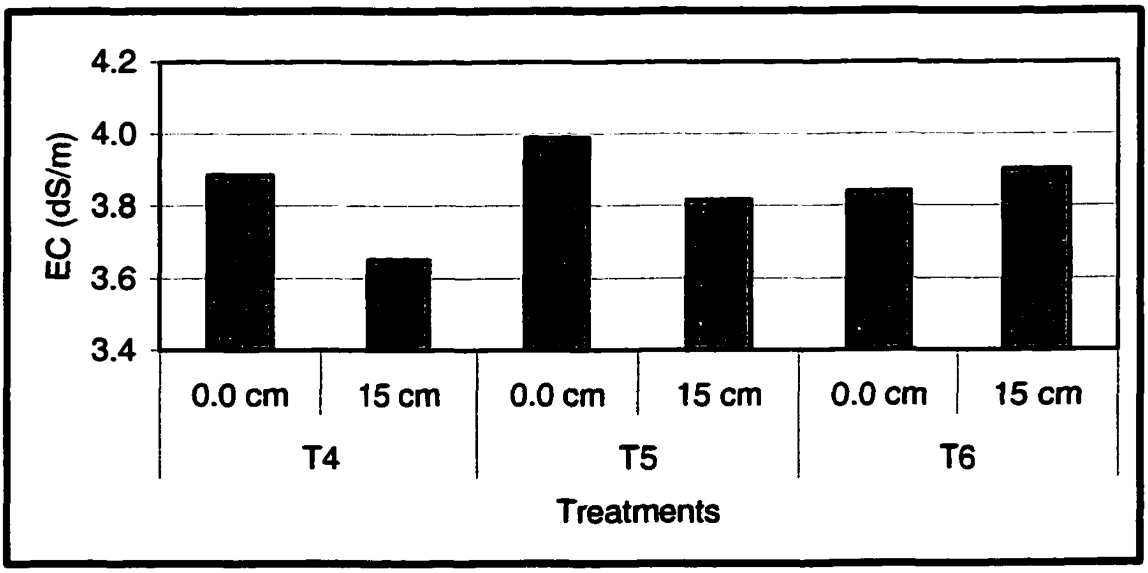

Figure 4.21. Predicted average accumulated salt in the root zone for the 3 day irrigation interval treatments, 1999 season.

The model calculations confirm that the highest leaching fraction results in the lowest level of accumulated salt in the active root zone, which is the expected result. In the deficit irrigation treatments, most of the salt that accumulated in the root zone was probably due to the shortage of irrigation water. Furthermore, most of the accumulated salt that was left behind by evapotranspiration during the growing season remained in the profile, under deficit irrigation treatments for both irrigation frequencies.

4.3.1.2 Comparison between the simulated and observed data.

There are several studies concerned with comparative mathematical models to evaluate model performance as discussed previously. A model is a good representative of accuracy if it can be used to predict within calibrated and validated ranges. The model performance for observed and predicted salt concentration in the crop root zone profile used a test statistic to compare measured data against simulated results of salt concentration. These comparisons included relative error (RE), and root mean square error (RMSE), and the index of agreement (d), Willmott (1982). These statistics can be sensitive to error especially from small numbers of observations. The comparison between the predicted and observed data of salt concentration for the 1999 season is illustrated in Table 4.6 and Figures A.1 and A.2, in Appendix A. The table indicates the index of agreement (d), Willmott (1982), which showed good agreement between the observed and computed salt concentrations in most of the treatments, especially under the emitter directly. The highest agreement between the observed and computed salt concentrations were found for the seven days irrigation interval under 124%ET treatment. However, for the three day irrigation interval, the highest agreement was obtained under 116%ET treatment. The least agreement was obtained under the deficit treatment (100%ET) for the seven day irrigation interval. These results may have been affected by the rainfall during the growing season which caused leaching of the salt and fertilizer from the active root zone and reduced the effect of the irrigation intervals. The highest value of simulated salt accumulation was clearly found at a depth of 30-60 cm in both directions: vertically under the emitters and horizontally midway between the emitters. On the other hand, the lowest value of simulated salt concentration was at a depth of 0-30 cm for both directions under the field experiments and the calculated data by the model. These results encourage the use of the model to predict the depth of salt accumulation under trickle irrigation. The124%ET treatment irrigated, every seven days, had the greatest performance agreement by relative error (6%, and 7%) and d (89 and 88) under the emitters and midway between the emitters, respectively. However, for the 116%ET treatment, the greatest agreement between the observed and simulated salt accumulation in the root zone was for the 3 day irrigation interval where the relative error was 8%, and 7%, and d values were 82, 83 below the emitters and midway between the emitters respectively.

The conclusion is that for long irrigation intervals, the 124%ET treatment demonstrated the greatest model performance agreement between the field measurements and calculated data of the salt distribution at different depth levels. On the other hand, the deficit irrigation (100%ET) treatment produced the lowest agreement under the long irrigation interval. In short irrigation intervals (such as 3 days) the model had good agreement with observed and simulated data under the 116%ET treatments compared to others. The poorest agreement of observed salt concentration and simulated salt concentration which obtained in some treatments may be due to the addition fertilizer which applied to the field experiment during he growing season. Overall, the HYDRUS-2D model provides reasonable results under trickle irrigation management for sweet corn, and is useful to predict salt accumulation and distribution in the root zone.

4.3.2 2000 growing season

4.3.2.1 Simulated prediction of salt distribution

Some modifications were done for some factors of the treatments. These modifications, used as input data for the model to predict the salt accumulation in the root zone, included the amount of irrigation water, irrigation frequency, and space between the soil samples taken in both the vertical and horizontal directions. The depths of the soil samples were also adjusted to smaller increments to better investigate the accumulated salt in the lower levels of the profile. The predicted concentration of the salt was investigated for vertical directions every 15 cm from 0 cm to 90 cm and midway between the laterals at 37.5 cm, at the same depths. Table A.4, in Appendix A illustrates the average simulated salt concentration in the root zone calculated by Hydrus-2D for 2000 growing season. As shown in Figures 4.22 and 4.23 , the greatest predicted values of salt accumulation occurred at a depth of 15-60 cm in most of the treatments under the emitters. However, the lowest salt accumulation occurred at 0-15 cm for the 2 day irrigation interval compared with other treatments for the 7 day irrigation interval.

Visually, the treatments that were irrigated after 2 days showed the greater uniformity of salt accumulation in the root zone compared with treatments that were irrigated after 7 days. Generally, the highest average values of salt concentration were predicted under 115%ET, to occur midway between the lateral tubes compared with others as shown in Figures 4.24 and 4.25.

Table 4.6. Comparison between the simulated and observed salt accumulation in the root zone for 1999 treatments under trickle irrigation.

Treatments	Depth (cm)	Simulation data (ECe)	Observation (ECe)	RMSE	RE %	Ave. RE %	d
-------7 day irrigation interval-------							
	0.0-30	3.62	3.51	0.12	3.24		
T1, (124%)	30-60	4.15	3.80	0.35	9.46	6	89
0.0 cm	60-90	3.90	3.80	0.10	2.70		
	0.0-30	3.37	3.40	0.03	0.82		
T1, (124%)	30-60	4.14	3.72	0.42	11.50.	7	88
15 cm	60-90	3.90	3.84	0.06	1.64		
	0.0-30	3.97	3.62	0.37	9.82		
T2, (116%)	30-60	4.28	3.81	0.48	12.74	9	74
0.0 cm	60-90	4.02	3.90	0.12	3.19		
	0.0-30	3.61	3.53	0.11	2.92		
T2, (116%)	30-60	4.30	3.80	0.50	13.27	8	83
15 cm	60-90	4.02	4.01	0.02	0.53		
T3, (100%)	0.0-30	3.24	3.50	0.26	7.16		
0.0 cm	30-60	4.24	3.61	0.65	17.89	13	63
	60-90	4.28	3.82	0.48	13.21		
T3, (100%)	0.0-30	3.43	3.52	0.07	1.94		
015 cm	30-60	4.28	3.63	0.68	18.89	12	64
	60-90	4.02	3.72	0.32	8.89		
-------3 days irrigation interval-------							
T4, (124%)	0.0-30	3.77	3.46	0.31	8.54		
0.0 cm	30-60	4.06	3.64	0.42	11.57	8	81
	60-90	3.83	3.79	0.04	1.10		
T4, (124%)	0.0-30	3.02	3.51	0.48	13.33		
15 cm	30-60	4.11	3.60	0.51	14.17	11	64
	60-90	3.83	3.70	0.13	3.61		
T5, (116%)	0.0-30	3.82	3.49	0.33	8.75		
0.0 cm	30-60	4.18	3.79	0.39	10.34	8	82
	60-90	3.97	4.03	0.06	1.59		
T5, (116%)	0.0-30	3.27	3.48	0.21	5.56		
15 cm	30-60	4.21	3.84	0.37	9.80	7	83
	60-90	3.97	4.01	0.04	1.06		
T6, (100%)	0.0-30	3.72	3.61	0.11	2.93		
0.0 cm	30-60	3.90	3.78	0.12	3.19	3	80
	60-90	3.90	3.89	0.01	0.27		
T6, (100%)	0.0-30	3.47	3.54	0.07	1.85		
15 cm	30-60	4.24	3.80	0.44	11.63	7	73
	60-90	4.00	4.01	0.01	0.26		

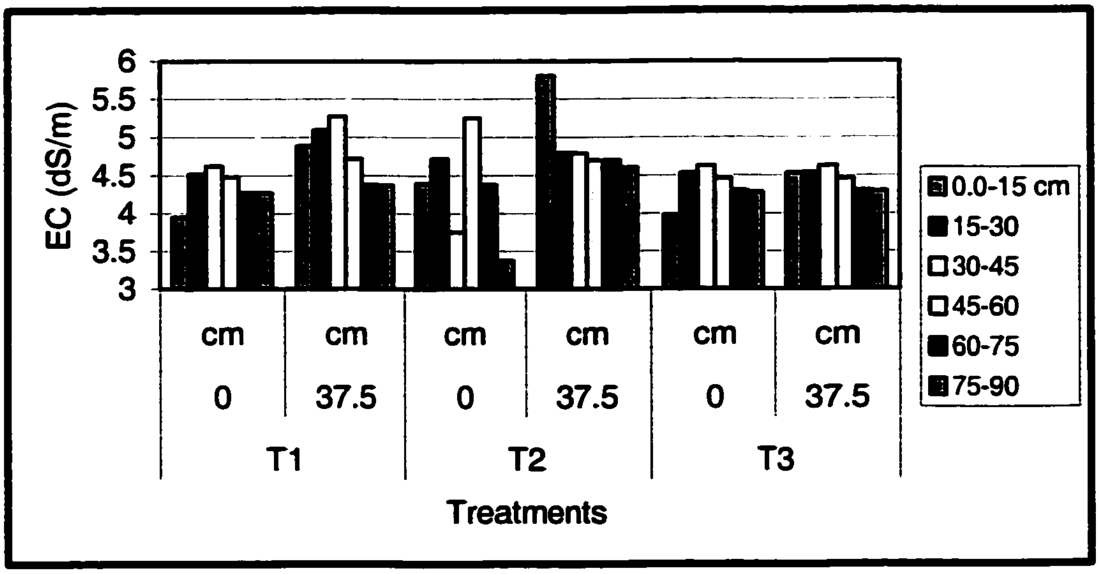

Figure 4.22. Simulated salt distribution during the 2000 growing season at different points of the root zone (vertically and horizontally) for the treatments irrigated every 7 days.

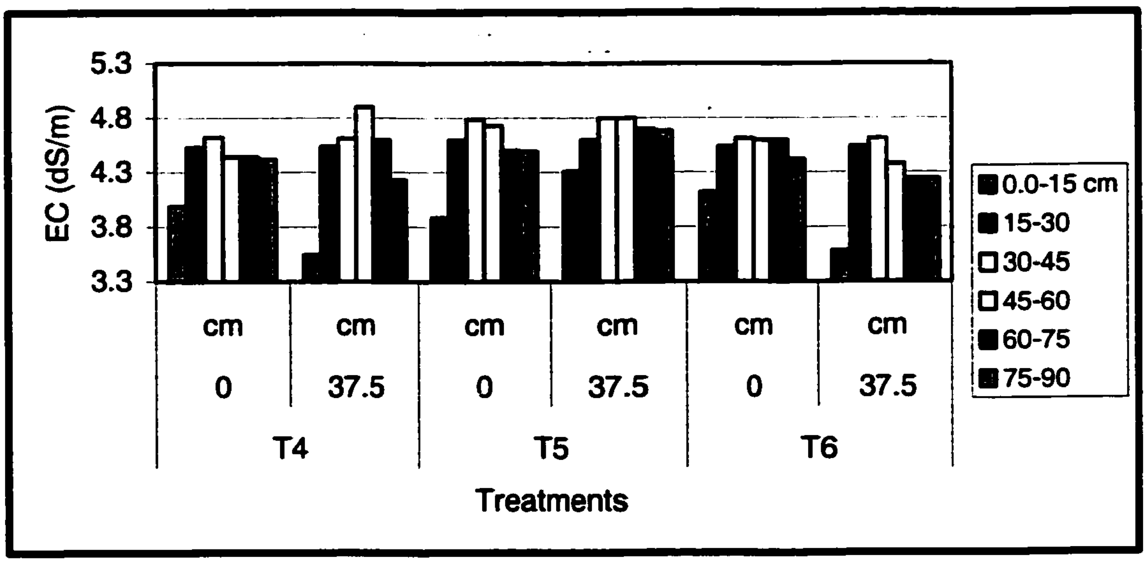

Figure 4.23. Simulated salt distribution during the 2000 growing season at different points of the root zone (vertically and horizontally) for treatments irrigated every 2 days.

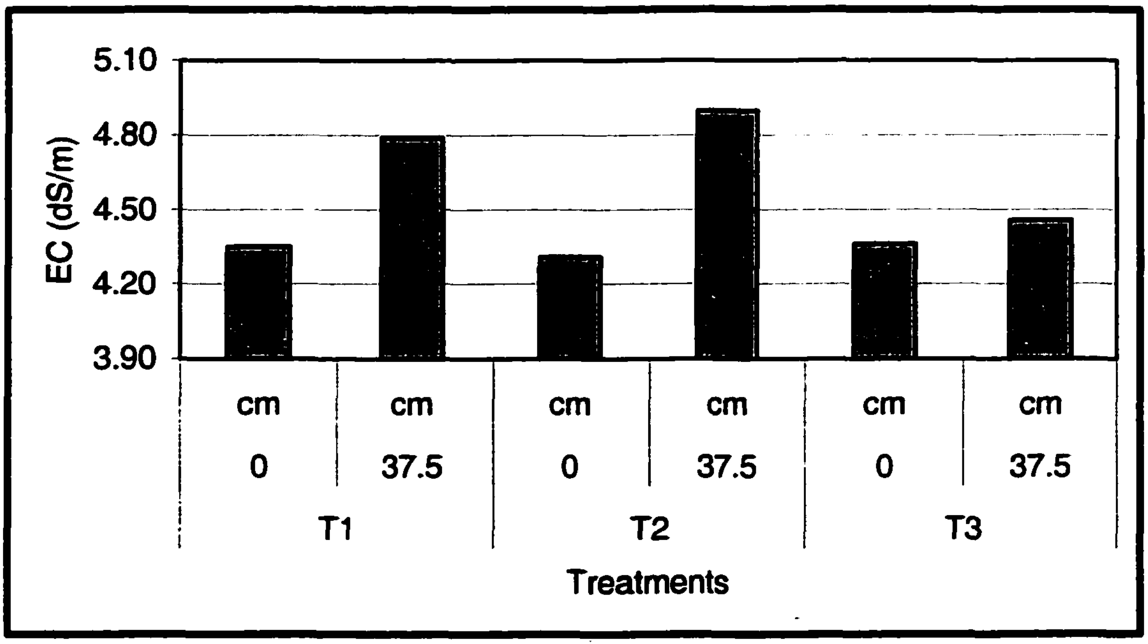

Figure 4.24. Simulated average salt accumulation in the root zone for the 2000 growing season for the treatments irrigated every 7 days.

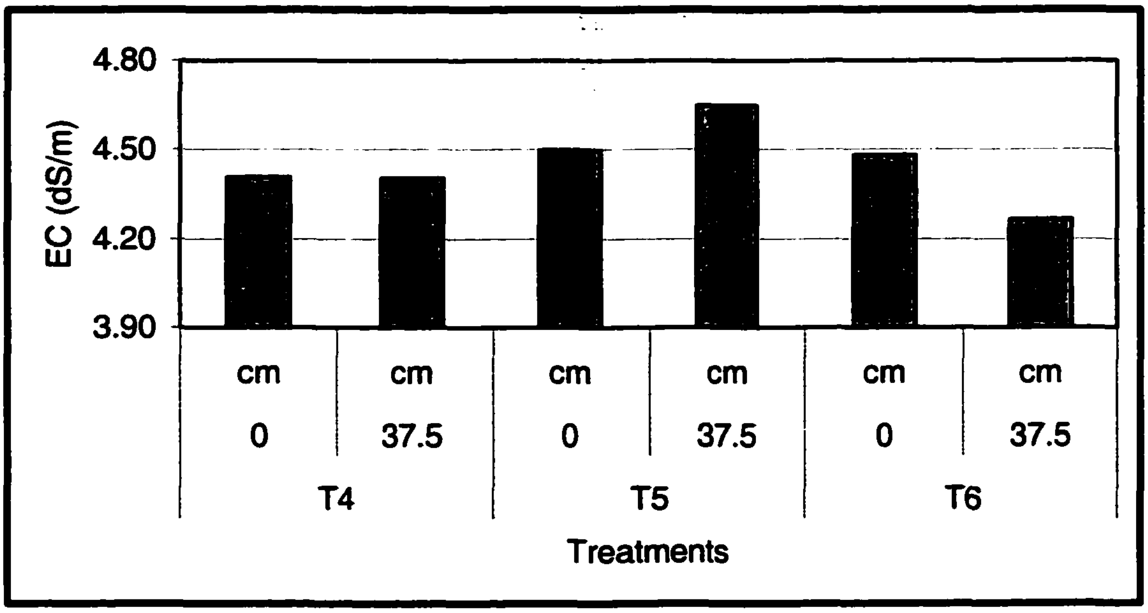

Figure 4.25. Simulated average salt accumulation in the root zone for the 2000 growing season for treatments irrigated every 2 days.

4.3.2.2 Comparison between the simulated and observed data

The comparison between the simulated and observed salt distribution data in the root zone is presented in Tables 4.7 and 4.8. Both tables summarize the three statistics: root mean square error (RMSE), relative error (RE), and index of agreement (d) (Willmott, 1982). The values of the salt accumulation under trickle irrigation in the field experiment in 2000 compared with the model calculation, using the same climatic conditions and soil physical and chemical properties as the boundary and initial conditions, indicated that the highest agreement was found under the greatest amount of irrigation water (130%ET) for both irrigation intervals as shown (also see Figures A.3 and A.4 in Appendix A). However, the lowest agreement was obtained under the deficit irrigation (100%ET treatments) for both irrigation intervals. The greatest amount of irrigation water (130%ET treatment) irrigated every 7 days resulted in the lowest relative error (7% and 7%), and highest index of agreement (81 and 78) directly under the emitters and midway between the lateral tubes, respectively. Furthermore, the RE and d agreement for the same treatment (130%ET) between the model calculated data and observed data for the two day interval was 6% and 11%, and 71 and 53 under the emitters and midway between the lateral tubes. However, the 115%ET and 100%ET produced had poor agreement between the simulated and observed values of salt accumulation compared to the 130%ET treatment. In all treatments, the greatest agreement between the calculated data and observed data occurred directly under the emitters. The salt distribution pattern around the emitters is dependent on the volume of irrigation water, the emitter flow rate, initial and boundary conditions, soil physical and chemical properties and their spatial distribution, root activity, and irrigation management. The extent of temporal variations in salt concentration was high at the 30-60 cm depth due to the slow infiltration of the clay soil, redistribution of salt patterns, and root zone extraction intensities. The RE showed more agreement compared to index agreement (d) in most of the results. This result may be due to the high sensitivity of (d) index compared to RE.

Generally, observed and simulated salt accumulation were investigated using relative error (RE) and the index (d) of agreement (Willmott, 1982) in two experimental seasons. The agreement of observed and simulated average values of salt accumulation was good for treatments 124%ET and 116%ET in the 1999 growing season irrigated every 7 and 3 days, respectively, and 130%ET for the 7 day interval in 2000. The model performance was good for high salinity concentrations under the emitters for most of the treatments during the cropping seasons, but less acceptable midway between the emitters and the lateral tubes. Poor agreement between the observed and simulated salt concentration increased by increasing the distance between the emitters and lateral tubes. This was probably due to model physical characteristics and the short length of the irrigation season, which did not allow the salt to accumulate in the top of the soil surface midway between the irrigation water sources. Comparisons between observed and simulated salt accumulation in the root zone showed the power of the HYDRUS-2D model, to predict soil EC under trickle irrigation management for sweet corn in some treatments and could be suitable for similar crops. The program calculation and performance agreement is absolutely dependent on the boundary and initial conditions that are entered as input data.

Table 4.7. Comparison between simulated and observed salt accumulation in the root zone for treatments irrigated every 7 days, 2000 season.

Treatments	Depth	Simulation	Observation	RMSE	RE	Ave. RE	d
	(cm)	dS/m	dS/m		%	%	
T1, (130%) 0 cm	0-15	3.95	3.53	0.42	8.9	7	81
	15-30	4.52	4.21	0.31	6.5		
	30-45	4.62	4.56	0.06	1.4		
	45-60	4.48	4.72	0.24	5.5		
	60-75	4.27	4.80	0.53	12.2		
	75-90	4.27	4.36	0.09	2.1		
T1, (130%) 37.5 cm	0-15	4.89	5.07	0.18	3.7	7	78
	15-30	5.10	4.65	0.45	9.2		
	30-45	5.28	4.85	0.43	9.8		
	45-60	4.72	4.84	0.12	2.5		
	60-75	4.38	4.90	0.52	10.9		
	75-90	4.37	4.40	0.03	0.6		
T2, (115%) 0 cm	0-15	4.39	4.29	0.10	1.9	15	62
	15-30	4.72	4.52	0.20	4.1		
	30-45	3.75	4.73	0.02	0.4		
	45-60	5.26	5.27	0.01	0.2		
	60-75	4.38	4.90	0.52	11		
	75-90	3.37	4.64	1.27	28.9		
T2, (115%) 37.5 cm	0-15	5.80	5.96	0.07	1.2	9	45
	15-30	4.80	4.81	0.01	0.2		
	30-45	4.79	4.79	0.00	0.0		
	45-60	4.70	5.65	0.95	18.2		
	60-75	4.70	5.38	0.68	13		
	75-90	4.60	4.76	0.16	3.1		
T3, (100%) 0 cm	0-15	3.97	4.13	0.16	3.4	11	64
	15-30	4.53	5.07	0.54	11.1		
	30-45	4.63	5.11	0.48	9.9		
	45-60	4.46	5.03	0.57	11.7		
	60-75	4.30	4.97	0.67	13.8		
	75-90	4.28	4.90	0.62	12.7		
T3, (100%) 37.5 cm	0-15	4.53	5.19	0.66	13.1	12	35
	15-30	4.54	4.97	0.43	8.5		
	30-45	4.63	5.05	0.42	8.3		
	45-60	4.46	4.89	0.43	8.5		
	60-75	4.30	5.00	0.70	13.9		
	75-90	4.29	5.20	0.91	18.0		

Table 4.8. Comparison between simulated and observed salt accumulation in the root zone for treatments irrigated every 2 days, 2000 season.

Treatments	Depth	Simulation	Observation (Ece)	RMSE	RE	Ave. RE	d
	cm	dS/m	dS/m		%	%	
	0-15	3.99	3.65	0.34	7.60		
	15-30	4.53	4.54	0.01	0.20		
T4, (130%)	30-45	4.62	4.75	0.13	0.30		
0 cm	45-60	4.44	4.34	0.10	2.20	6	71
	60-75	4.44	4.82	0.38	4.50		
	75-90	4.42	4.79	0.37	8.30		
	0-15	3.54	4.66	1.12	23.50		
	15-30	4.54	4.71	0.17	3.60		
T4, (130%)	30-45	4.61	4.75	0.14	2.90	11	53
37.5 cm	45-60	4.90	5.01	0.11	2.30		
	60-75	4.6	4.65	0.10	1.10		
	75-90	4.23	4.85	0.62	13.0		
	0-15	3.88	4.60	0.7	15.1		
	15-30	4.60	4.97	0.4	7.8		
T5, (115%)	30-45	4.79	4.53	0.3	5.4	9	67
0 cm	45-60	4.73	4.87	0.1	2.9		
	60-75	4.5	5.10	0.6	12.6		
	75-90	4.49	4.56	0.6	1.5		
	0-15	4.31	5.55	2.24	43.2		
	15-30	4.60	4.64	0.04	0.8		
T5, (115%)	30-45	4.80	4.89	0.09	1.7	13	13
37.5 cm	45-60	4.80	5.51	0.71	13.7		
	60-75	4.70	5.57	0.87	16.8		
	75-90	4.68	4.97	0.27	5.2		
	0-15	4.12	4.17	0.05	1.1		
	15-30	4.54	4.88	0.34	7.11		
T6, (100%)	30-45	4.61	5.00	0.39	8.2	8	65
0 cm	45-60	4.60	5.19	0.59	12.3		
	60-75	4.60	5.00	0.40	8.4		
	75-90	4.42	4.46	0.04	0.80		
	0-15	3.58	5.36	1.78	34.6		
	15-30	4.54	5.19	0.65	12.6		
T6, (100%)	30-45	4.61	4.83	0.22	4.3	19	12
37.5 cm	45-60	4.38	5.41	1.03	20.3		
	60-75	4.24	5.09	0.85	16.5		
	75-90	4.24	5.00	0.76	14.77		

4.4 Model sensitivity analysis

In this part of the chapter, HYDRUS_2D model sensitivity was evaluated using three different soil textures with different hydraulic conductivity parameters as show in Table 4.9. Two irrigation regimes were evaluated (100%ET, irrigated every seven days, and 130%ET irrigated every 2 two days) and field and irrigation salinity values were used as initial and boundary conditions.

Table 4.9 Parameter values of hydraulic properties of soil.

Soil	Ks (cm/day)	θ_r	θ_s	α	n
*Clay soil	5.97	0.068	0.38	.008	1.09
Clay soil	4.8	0.068	0.38	.008	1.09
Clay loam	6.24	0.095	0.41	.019	1.31
Silt soil	6.0	0.034	0.46	0.016	1.37

*Field soil parameters.

The results show that the model is sensitive to soil texture and hydraulic conductivity parameters, irrigation amount and interval as show in Figures 4.26 to 4.29. These three factors have great affect on the agreement between measured and simulated salt accumulation in the root zone. As show in Figures 4.30 and 4.31 and in Tables A.5 and A.6 (Appendix A), the agreement directly under the emitters is always greater than midway between the emitters for the clay soil simulated.

Agreement midway between the laterals is somewhat improved using other the hydraulic properties for clay loam soil under the driest conditions (100%ET, 7 day interval), but simulated salt accumulation in the root zone gives a poorer result overall. There is very little difference between the simulated salt distributions for the two clay soils even though the saturated hydraulic conductivity of one is 24% higher than the other. This is an important result given the small number of measurements that the K_s value for our field soil was based upon. Simulations using the field-measured K_s value resulted in test agreement with measured salt accumulations both under the emitter and midway between the laterals. This gives us a measure of reliability in using the field-measured parameters in the previously discussed comparisons and in the next chapter on system design option.

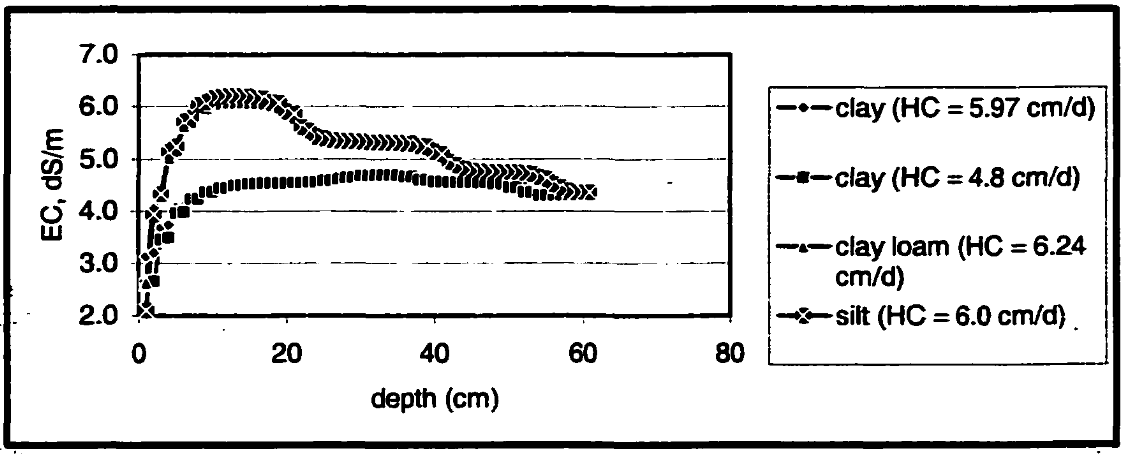

Figure 4.26. Model sensitivity analysis for EC for different soil texture for 7 day irrigation interval (100%ET), below the emitter.

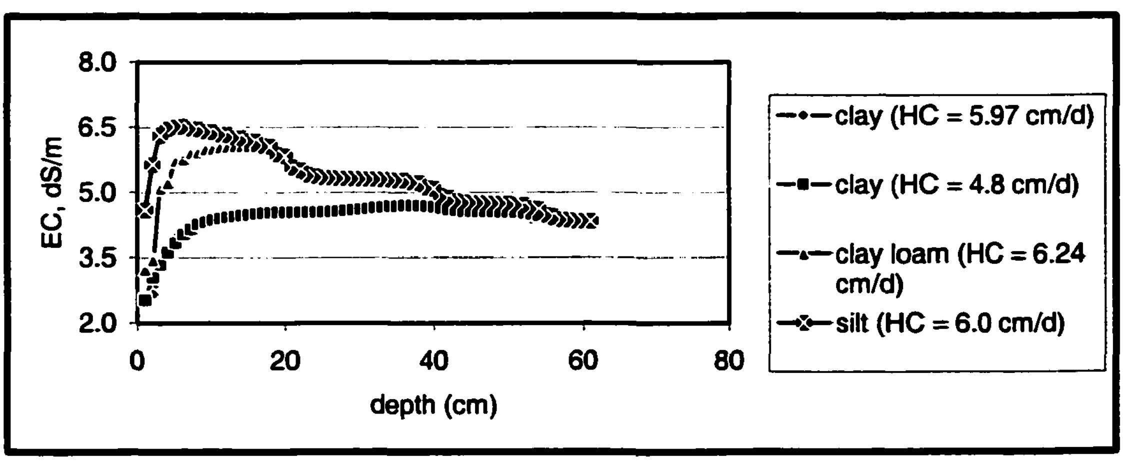

Figure 4.27. Model sensitivity analysis for EC for different soil texture for 7 day irrigation interval (100%ET), midway between the emitters.

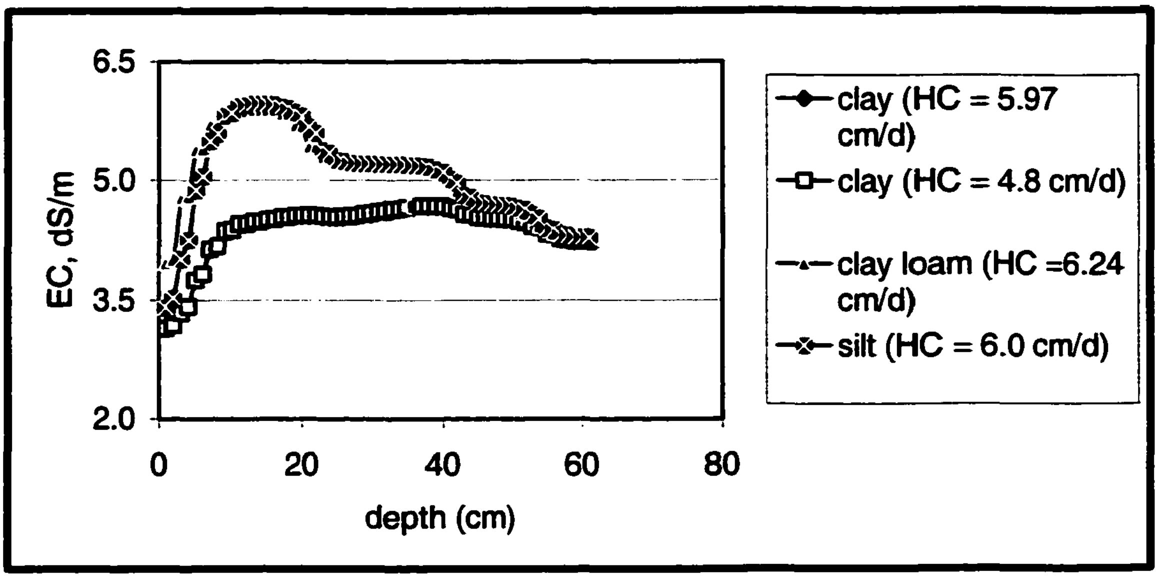

Figure 4.28. Model sensitivity analysis for EC for different soil texture for 2day irrigation interval (130%ET), below the emitter.

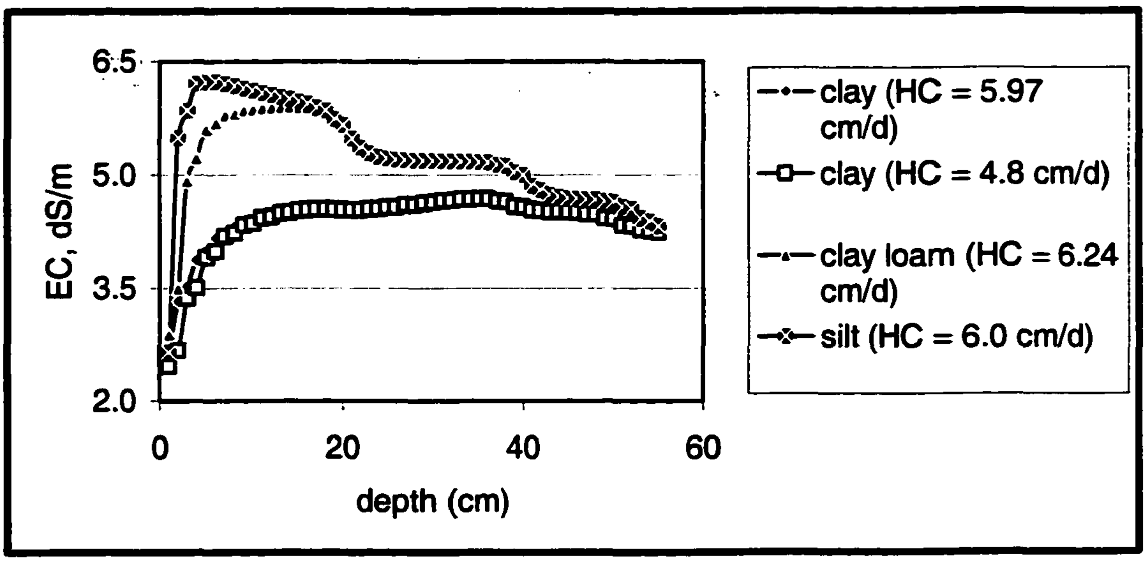

Figure 4.29. Model sensitivity analysis for EC for different soil texture for 2 day irrigation interval (130%ET), midway between the emitters.

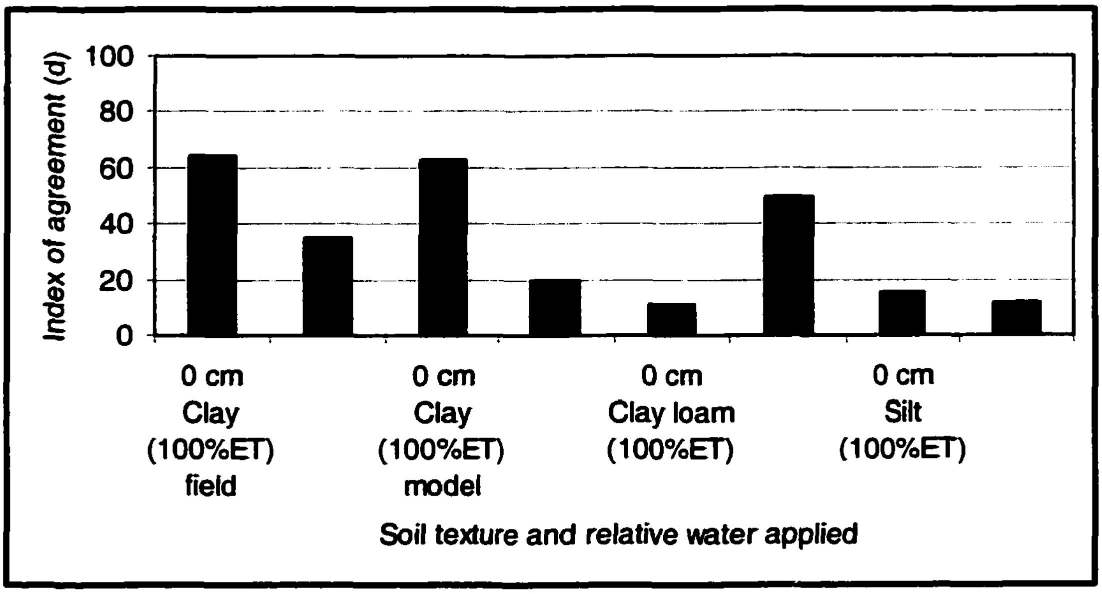

Figure 4.30. Comparison of simulated and observed salt concentration to evaluate model sensitivity under different soil texture for 7 day irrigation interval.

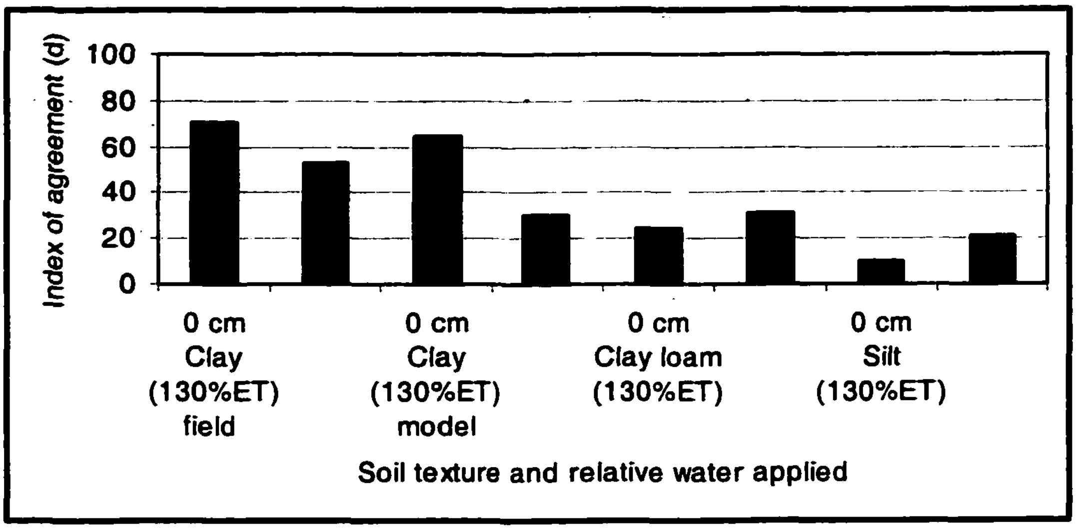

Figure 4.31. Comparison of simulated and observed salt concentration to evaluate model sensitivity under different soil texture for 2 day irrigation interval.

CHAPTER 5

DESIGN OPTIMIZATION

5.1 Introduction

This chapter describes the use of the HYDRUS-2D model to predict the optimal trickle irrigation system design for the management of salinity in row crops. The model used to predict root water uptake was based on field conditions that were entered as boundary and initial conditions. Parameters used in the simulation process include an average of climatic conditions from three years (1998, 1999, and 2000) at the horticultural experiment weather station in northeastern Fort Collins, Colorado. The input parameters also included soil physical and chemical properties, electrical conductivity of the irrigation water, amount of irrigation water, different leaching fractions, and irrigation intervals. The input parameters allowed the model to predict transpiration of sweet corn under trickle irrigation based on different treatments.

There are 72 treatments that have been established in this chapter based on the interaction of three variables: amount of irrigation water, irrigation intervals, and the space between the emitters and the lateral tubes. The treatments were designed as follows: 85%, 100%, 115%, and 120%ET, and each of the amounts of irrigation water was carried out at 15, 30, 40, 45, 70, and 100 cm distance between the emitters and lateral tubes, for 1, 3, and 7 day irrigation interval. The treatment design is illustrated in Tables B.1, B.2 and B.3 in Appendix B. The predicted ratio of Ta/Tp was used to evaluate the optimal design. This designt was considered to be the combination of variables which produced the highest ratio of accumulated calculated transpiration (Ta) to potential transpiration (Tp) which in turn, is used to estimate relative yield (RY) in these modeled treatments. The relative yield was calculated as per Doorenbos and Kassam (1979). They reported relative yield based on ET relationships for many crops and developed the following equation:

$$RY = 1 - k + k\,(ET/PET)$$

where RY is relative yield;

k is a crop specific yield response coefficient.

They suggested the value of k for corn to be 1.25. Cardon and Letey (1992) considered evapotranspiration (ET) to be equivalent to actual transpiration (Ta), and potential evapotranspiration (PET) to be equivalent to potential transpiration (Tp) to estimate (RY) for their salinity model. The previous assumption will be used to estimate RY in this experiment, since HYDRUS-2D estimates transpiration instead of evapotransp-iration.

5.2 Results and discussion

5.2.1 Root water uptake and predicted relative yield

Root water uptake of sweet corn under different irrigation regimes of applied irrigation water during different irrigation intervals was investigated under a trickle irrigation system. The judgment on the best combination between irrigation interval, distances between the emitters and leaching fraction is dependent on the potential and the actual transpiration. The potential and actual transpiration have been considered based on the ratio between the actual and potential transpiration and the relative crop yield predicted. Prior to applying the HYDRUS-2D model, reference evapotranspiration based on water balance which was computed daily during the growing season from a weather station located at the field experiment site. The water balance included rainfall, irrigation water, and evapotranspiration. Tables B.1, B.2 and B.3 in Appendix B, present amounts of irrigation water and the ratios of the potential and simulated transpiration for the treatments. The results indicate that all three factors irrigation intervals, amounts of (irrigation water, and the space between the emitters) have an affect on the ratio of Ta/Tp, and consequently, on RY. The greatest values of Ta/Tp occurred under 1, 3, and 7 day irrigation interval treatments, respectively (Figures 5.1 to 5.7). According to the model output, the model was most sensitive to the distance between emitters and lateral tubes, and irrigation intervals. This is probably related to soil water availability and osmotic pressure. Low soil water content and osmotic pressure are additive in reducing water availability to the crop and reduce actual transpiration. This result could reflect the idea of maintaining the soil water content constant in the root zone to reduce the effect of the salt on the crop's extraction of water from the soil surface as stated by Beltrao and Ben Asher's (1997). Since crop yield is a function of the ratio of actual to potential transpiration, the yield reduction could be affected by salt and water availability in the root zone. Regardless of the irrigation interval, calculated RY was highest for small distance between the emitters as shown in Figures 5.8 to 5.10. Moreover, the relative calculated yield was ranked highest to lowest under the 1, 3, and 7 day irrigation interval respectively, as shown in Tables B1, B.2 and B.3 in Appendix B. The Tables show cumulative transpiration under the 1, 3, and 7 day irrigation intervals respectively. Also, some examples of input and output data files are shown in Tables B.4 to B.7 Appendix B.

Narrow spaces between the emitters produced the highest values of Ta/Tp and as is shown in Figures 5. 8 to 5.10. This result may be related to the relatively high evaporation and to the levels of salt accumulated in the active root zone midway between the emitters and lateral tubes which could occur under large spaces between the emitters and lateral tubes. On the other hand, the accumulated salt probably has a better chance to be leached from the active root zone under the emitters and lateral tubes that are set up at small spacing, which could increase the crop's actual transpiration. This result could lead to the general idea that increasing the spaces between the emitters, decreases the value of Ta/Tp, and consequently, the RY of the crops.

Different percentages of irrigation water caused small differences in the values of Ta/Tp and RY (Figures 5.5 to 5.10). Commonly, different amounts of applied water produced little difference in Ta/Tp and RY for the same irrigation interval. This may be due to the high efficiency of trickle irrigation systems which could maintain water content in the root zone. It was therefore concluded from this result that most of the irrigated water was consumed by the crop under deficit (100%ET) irrigation water, but by increasing the amounts of irrigation water to more than deficit (> 100%ET), some amounts of additional water could be drained out of the crop root zone.

In general, the results showed the highest ratios of the actual and potential transpiration in treatments that were irrigated for short irrigation intervals compared to those treatments which were irrigated for longer irrigation intervals. For all simulations, it appears that Ta/Tp was negatively affected by long irrigation intervals and large distances between the emitters. Since ratio of Ta/Tp could reflect the relative yield (RY), using HYDRUS-2D model calculated is powerful in predicting the optimum irrigation management for trickle irrigation.

Zhang and Elliott (1996) summarized factors which affected growth activity of plant root water uptake, such as water content, mechanical characteristics of soil solution, genetic characteristics and current physical status of the plant. From the previous results, the following points are apparent:

1) Treatments that were irrigated every day produced a higher ratio of Ta/Tp and RY compared to those treatments which were irrigated every 3 days or every 7 days;
2) The ratio of Ta/Tp and RY decreased by increasing the distance between the emitters and lateral tubes;
3) Regardly to the simulated results of the Ta/Tp and the RY for different treatments, the model has good ability to predict irrigation management for small distance between the emitters and lateral tubes and for row crops.

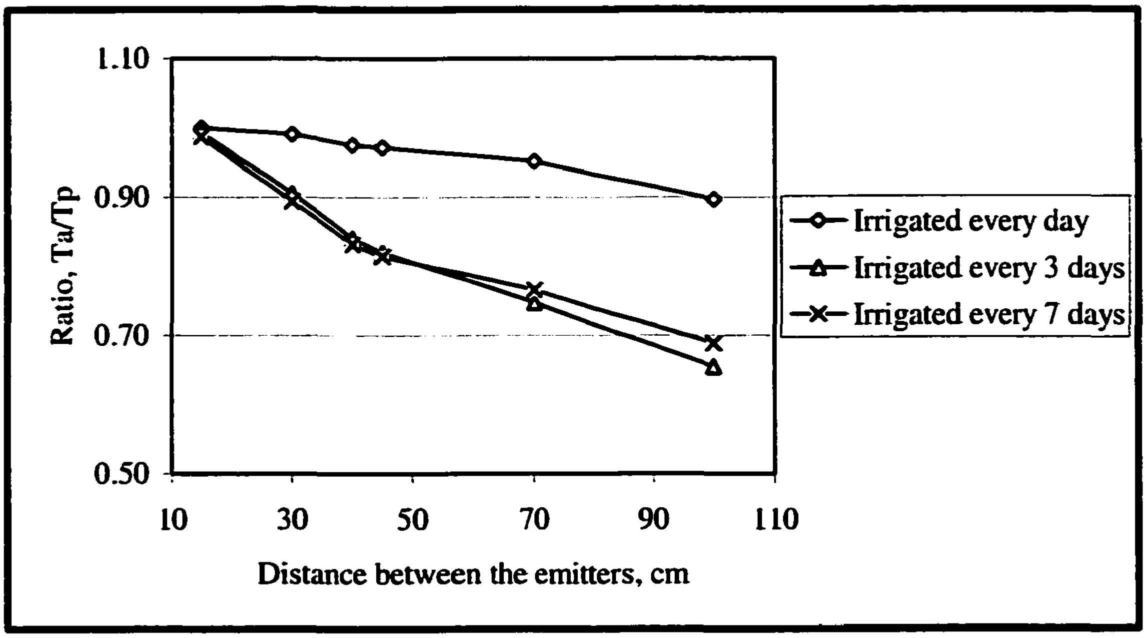

Figure 5.1. Ratio of Ta/Tp for the 85%ET treatment for different irrigation intervals and different distances between the emitters.

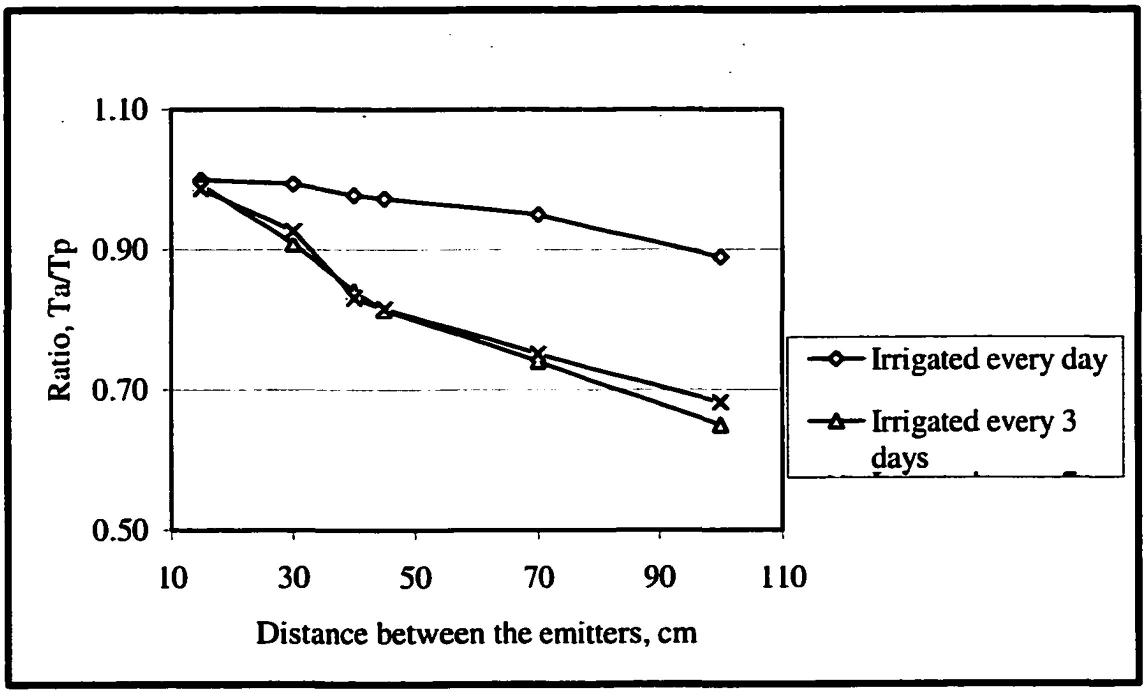

Figure 5.2. Ratio of Ta/Tp for the100%ET treatment for different irrigation intervals and different distances between the emitters.

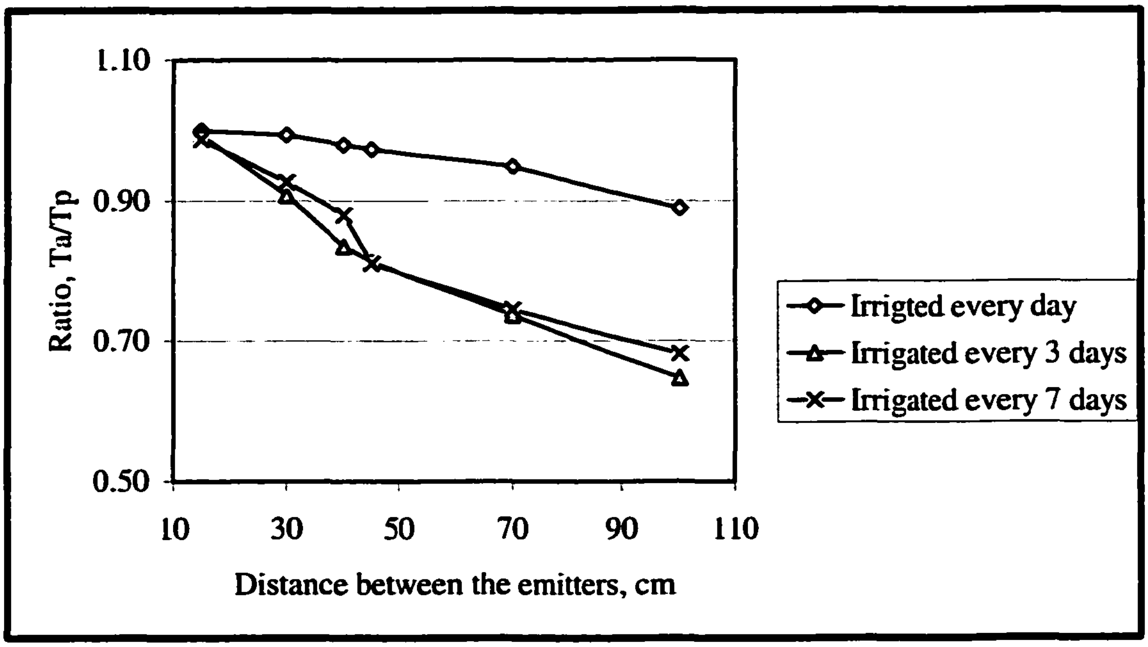

Figure 5.3. Ratio of Ta/Tp for the 115%ET treatment for different irrigation intervals and different distances between the emitters.

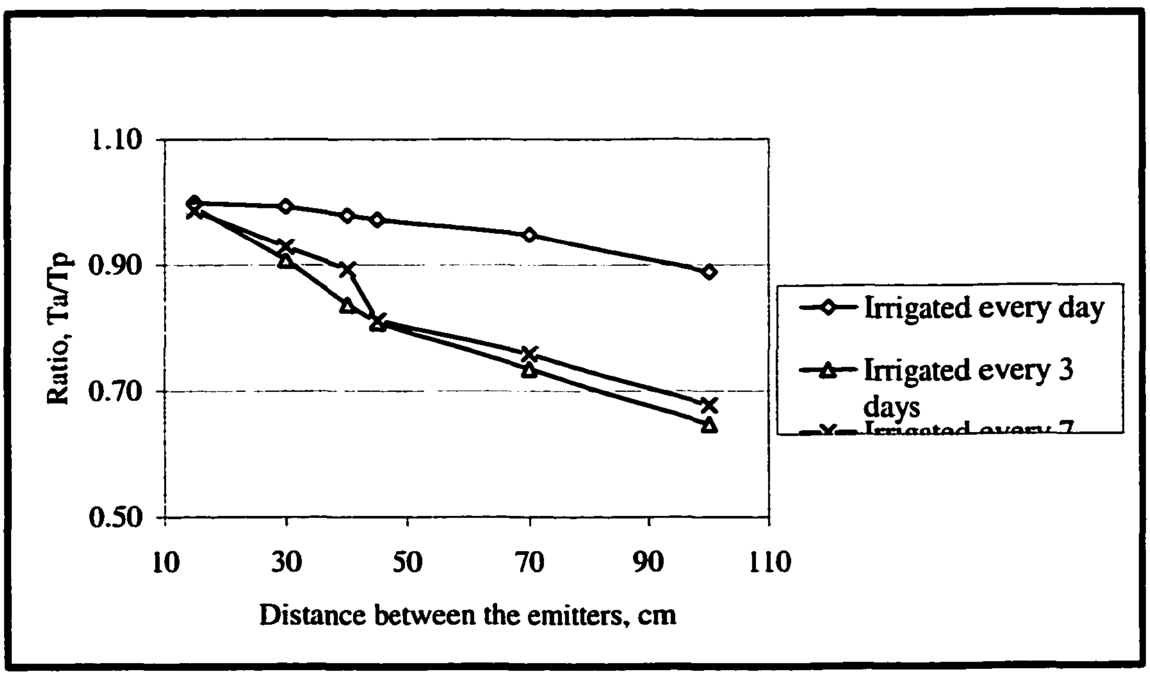

Figure 5.4. Ratio of Ta/Tp for the 120%ET treatment for different irrigation intervals and different distances between the emitters.

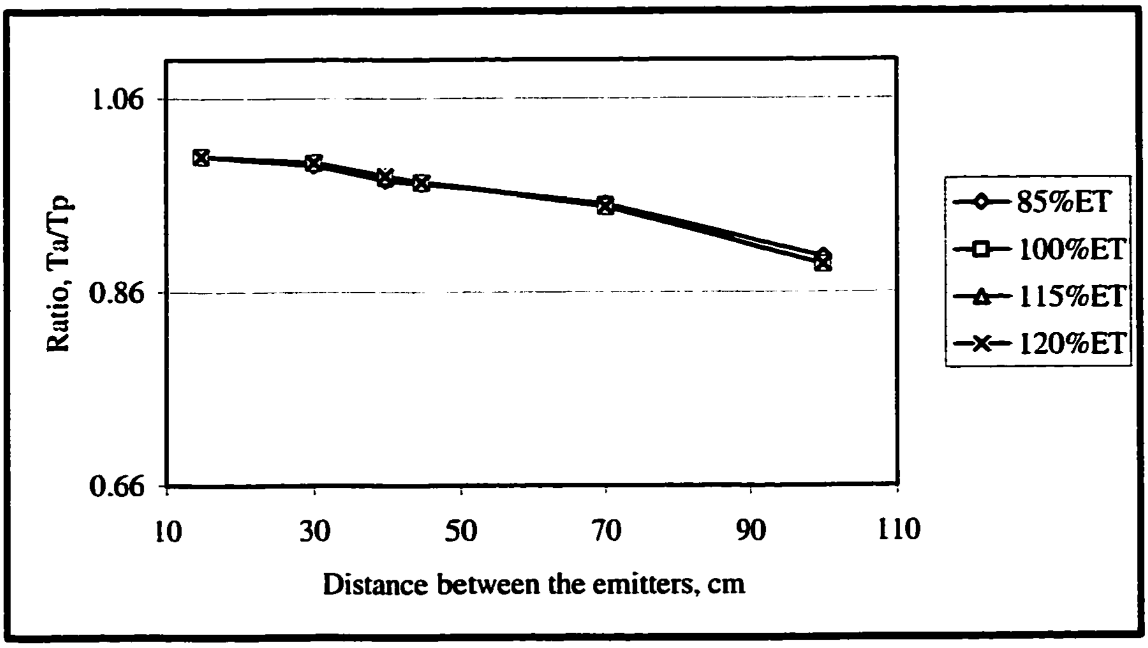

Figure 5.5. Ratio of Ta/Tp for the every day irrigation interval at different distances between the emitters.

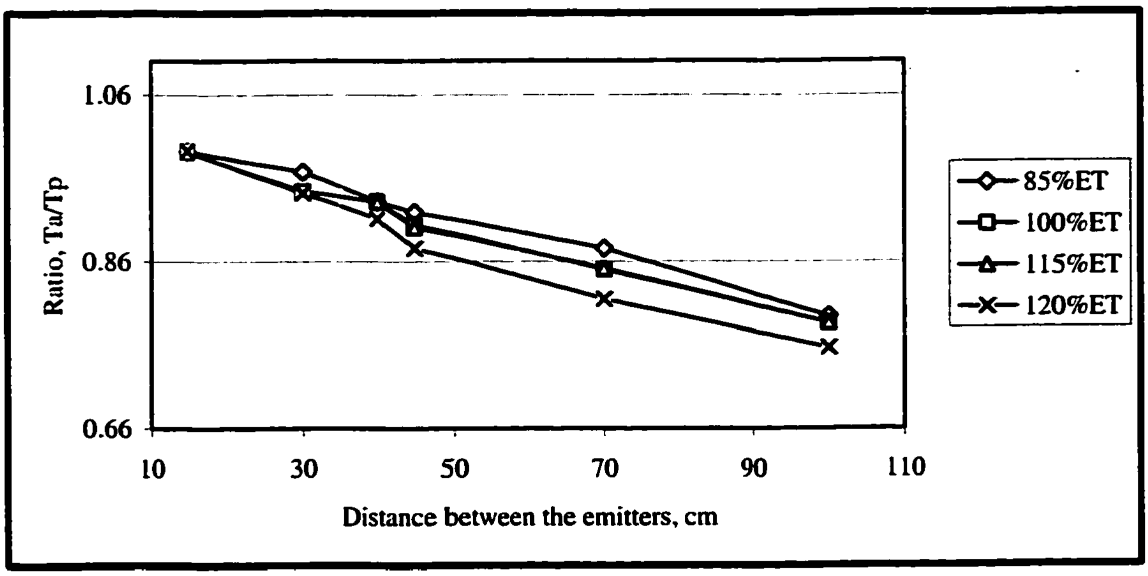

Figure 5.6. Ratios of Ta/Tp for the 3 day irrigation interval at different distances between the emitters.

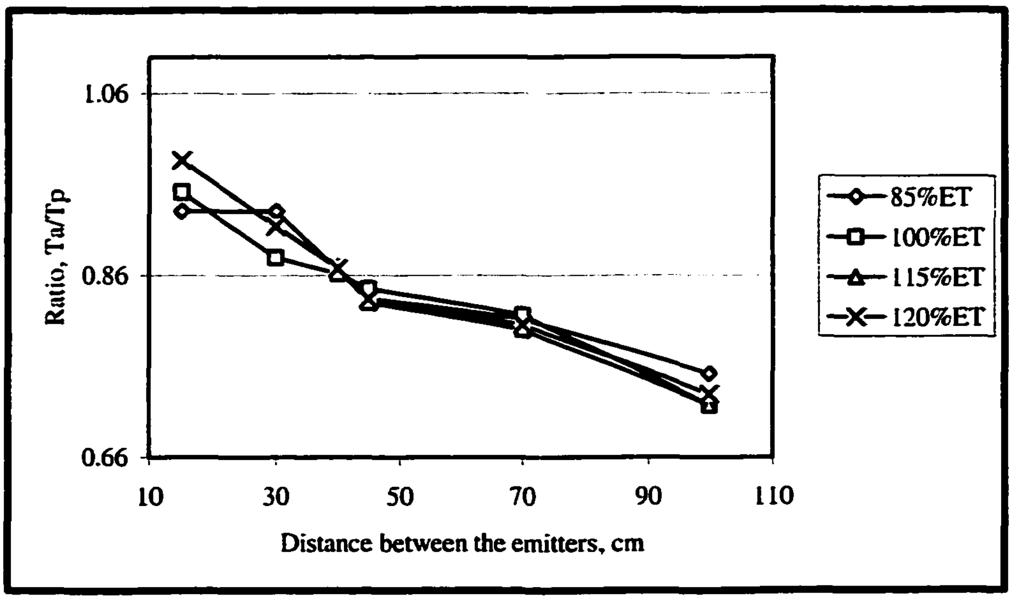

Figure 5.7. Ratios of Ta/Tp for the 7 day irrigation interval at different distances between the emitters.

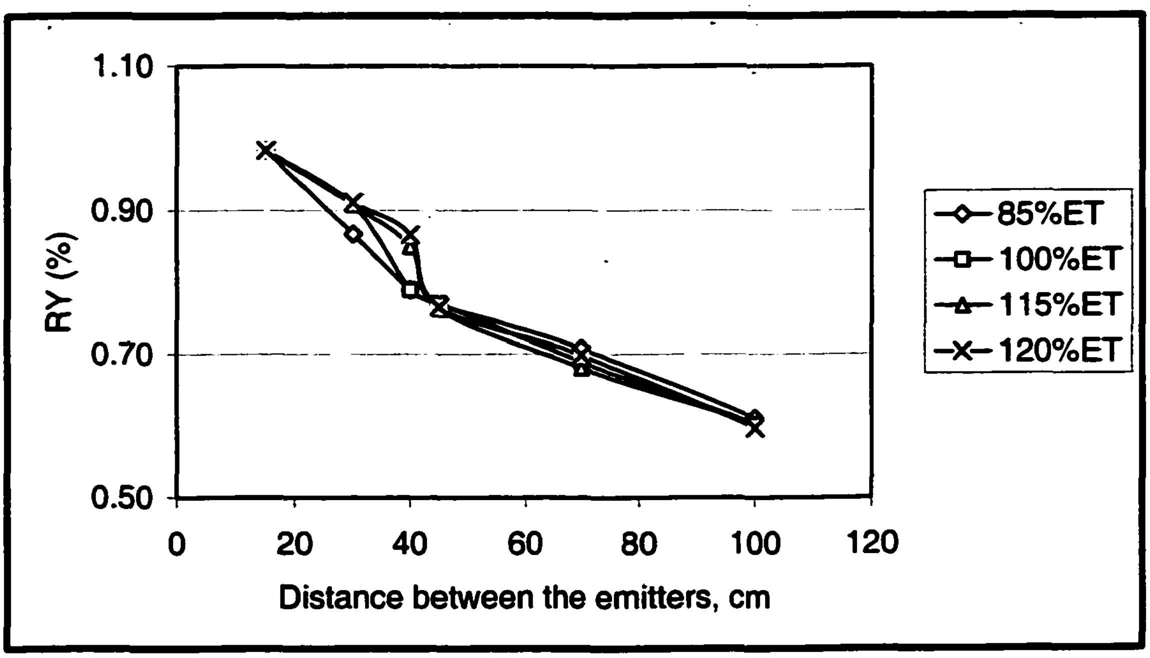

Figure 5.8. Relative yield (RY) at different amounts of irrigation water for every day irrigation interval.

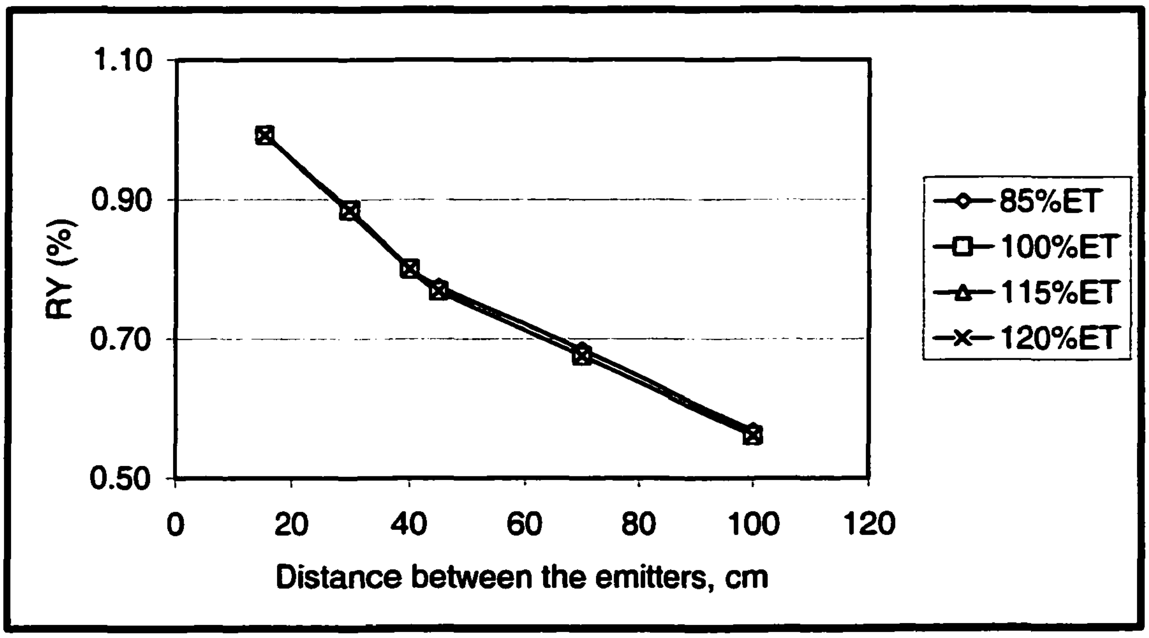

Figure 5.9. Relative yield (RY) at different amounts of irrigation water for 3 day irrigation interval.

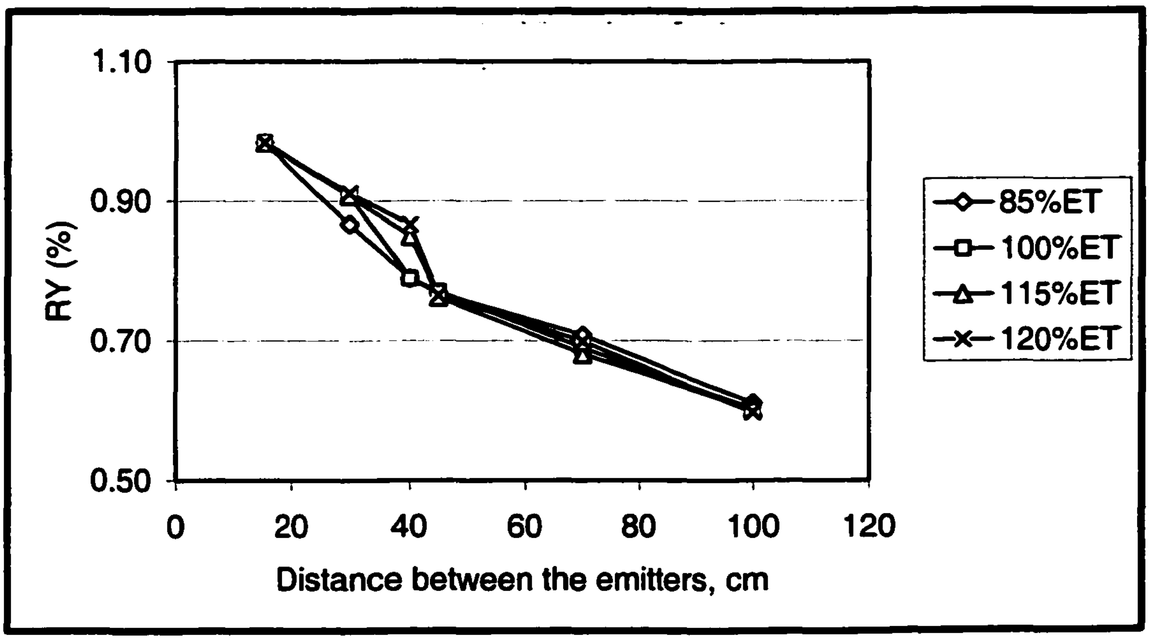

Figure 5.10. Relative yield (RY) at different amounts of irrigation water for 7 day irrigation interval.

CHAPTER 6

SUMMARY AND CONCLUSION

A study was conducted to investigate the effects of trickle (drip) irrigation management under saline conditions for sweet corn. The study concentrated on two main variables: leaching fraction and irrigation schedule. The study objective was to determine the optimum irrigation configuration to reduce salinity effects in the active root zone of the crop by estimating accurate amounts of irrigation water and irrigation scheduling and maximizing the crop yield and water use efficiency for field experiment. Also, comparisons of field experiment yield results with relative yield as estimated by the Mass and Hoffman (19977) and Keller and Bllienser (1990) models were investigated. In addition, this study compared salt accumulation in the active root zone based on field measurements with predictions by the HYDRUS-2D model when using the same climatic, soil physical and chemical conditions, and irrigation management parameters of the field experiments.

6.1 Summary

6.1.1 Field experiments

Field experiments were carried out for two growing seasons (1999 and 2000) at the Horticultural Experimental Station northeast of Fort Collins, Colorado. The experiments were carried out on an 840 m^2 irrigated field with a trickle irrigation system with a layout 30 cm between the emitters and 75 cm between the lateral tubes. The field was irrigated by ground water which had an EC of 3.2 dS/m. The field experiment consisted of six treatments: 100%, 116%, 124%ET irrigated every 3 days and 100%, 116%, 124%ET irrigated every 7 days in the 1999 growing season. In the 1999 growing season, the crop was planted on June 20, 1999 and harvested on September 6, 1999. Soil samples were taken three times during the growing season: at the beginning, mid-season, and at the end of the season immediately after harvest. Statistically, the interactions of treatments by depths, and treatments by sample location resulted in a significant difference in the electrical conductivity of soil samples. No significant differences were obtained in the average salt concentrations among the treatments. The results showed the lowest salt concentration under the 124%ET treatments, and the highest values of electrical conductivity were obtained under the deficit treatments (100%ET). Commonly, the greatest accumulation of salt in all treatments was obtained at a depth of 60-90 cm. In general, the three day irrigation interval produced the highest fresh ear yield. On the other hand, the greatest WUE occurred under the 100%ET treatment irrigated every three days compared to all 1999 growing season treatments. The results also indicated that the ranking of yield (highest to lowest) was 116%, 124%, and 100%ET.

Because statistical analysis did not show significant differences between the average EC of the treatments in the root zone, some adjustments were done for the 2000 growing season to increase the variation between the treatments. Changes were made in the amounts of irrigation water, irrigation interval, and the depth and location of soil samples. The irrigation amounts were 100%ET, 115%ET, and 130%ET, irrigated on both a 2 and 7 day interval. In the 2000 growing season, the crop was planted on June 15, 2000 and harvested on September 18, 2000. Significant differences occurred among the treatments in the soil EC. The results suggested that increasing the amounts of irrigation water decreased the salt concentration in the active root zone. Under the deficit treatment (100%ET), accumulated salt tended to occur in the soil surface midway between emitters. The greatest values of accumulated salt were 5.5 dS/m and 5.17 dS/m at the 15-30 cm and 30-60 cm depth obtained under the 100%ET and 115%ET treatments, irrigated after seven days, respectively. However, the greatest values of accumulated salt were 5.87 dS/m and 5.10 dS/m at depths of 0-30 cm and 60-75 cm for the 100%ET and 115%ET treatments, irrigated every two days, respectively. The lowest values of accumulated salt were obtained under the 130%ET treatment for both irrigation intervals. Total crop production was considered in the field study and indicated that the highest crop production of fresh ears was obtained under high irrigation frequency especially under the 115%ET treatment. On the other hand, the highest value of WUE occurred under the 100%ET treatments under both irrigation intervals. The WUE was 5.9, 7.4, and 7.9 kg/m^3 for the seven day irrigation interval, and 6.7, 7.9, 8.6 kg/m^3 for the two day irrigation interval under the 130%ET, 115%ET, and 100%ET, respectively. On the other hand, the highest relative yield was obtained under the 115%ET treatment for both irrigation intervals.

6.1.2 Modeling (HYDRUS-2D) effort

The climatic, soil physical and chemical properties, and irrigation schedule from the field experiments were used as input data for the HYDRUS-2D model which was used to evaluate the agreement between the observed and simulated data. Statistical interpretation in this study indicates the RE values of 10% or less are acceptable. However, RE less than 20% was considered poor agreement between the observed and simulated data. Furthermore, the index agreement (d) (Willmott, 1982) statistical values of 90-100, 80-90, and 70-80% were considered excellent, good, and acceptable performance respectively, but less than 70% was considered poor agreement.

In the 1999 growing season, the greatest predicted values of average accumulated salt occurred under the 100%ET treatment compared to other treatments, which was a logical result. But the greatest model agreement was obtained under the 124% ET treatment irrigated every seven days and the 116%ET treatment irrigated every three days. In general, the comparison between the observed and simulated soil EC was good in all treatments except the 100%ET irrigated after seven days, which was evaluated as poor agreement between the measured and simulated data probably related to water shortage and high osmotic potential.

Under the 2000 growing season conditions, the highest simulated values of average accumulated salt occurred under the 115%ET treatment irrigated every two days. The greatest agreement between the observed and simulated data was obtained under the 130%ET treatment for both irrigation intervals. The poorest agreement was indicated for the 100%ET treatments for both irrigation intervals. The comparison between the field results and the simulated accumulated salt levels showed that the greatest agreement occurred for the 1999 season compared to the 2000 season. This was probably related to the small space (between the emitters) between the soil samples that were taken between the emitters in the 1999 experimental field and the larger distance (between the lateral tubes) between the soil samples in the 2000 growing season.

6.1.3 Design optimization

Additional modeling exercises were conducted with HYDRUS-2D to determine the optimal design and management of a trickle irrigation system using same the irrigation water. The calculated ratio of Ta/Tp which was determined by the model. In all, 72 treatments were simulated using the model under clay soil conditions. Results of this modeling exercise the foloowing points:

1) Treatments that were irrigated every day produced a higher ratio of Ta/Tp and RY compared to those treatments which were irrigated every three days or every seven days;

2) The ratio of Ta/Tp and RY was reduced by increasing the distance between the emitters and lateral tubes;

3) According to the results of the HYDRUS-2D model, the model is an excellent tool to help detemine irrigation management system configuration for trickle irrigation for row crops under saline conditions in clay soil.

6.2 Conclusions

The results obtained during this research indicate that the amount of irrigation water is not the only critical factor in crop production with trickle irrigation on a clay soil, but that the most important factor is irrigation frequency. According to these results, high irrigation frequencies could maintain clay of soil water content to reduce the effect of osmotic pressure on crop water uptake. However, rainfall is another factor to be considered during the irrigation season in order to balance the salt leaching with fertilizer retention in the root zone. On the other hand, the highest values of WUE occurred under 100%ET for both seasons; however, the highest values of RY occurred under 116%ET and 115%ET for the 1999 and 2000 growing seasons irrigated every 3 and 2 days, respectively. Optimal trickle irrigation design and management can save water and increase crop production.

Additionally, using the HYDRUS_2D model can save cost and time in optimizing the design and management of a trickle irrigation systems for sweet corn and other row crops under clay soil and saline conditions. The model prediction of Ta/Tp and RY showed that the most critical factors for optimum irrigation design and management of trickle irrigation under saline conitions are the distance between the emitters and lateral tubes, and irrigation interval. The smaller the distance between the water application location (emitter) and the shorter the irrigation interval, the greater Ta/Tp and RY.

There is very little difference between the simulated salt distributions for the two clay soils even though the saturated hydraulic conductivity of one is 24% higher than the other. This is an important result given the small number of measurements that the K_s value for our field soil was based upon. Simulations using the field-measured K_s value resulted in test agreement with measured salt accumulations both under the emitter and midway between the laterals. This gives us a measure of reliability in using the field-measured parameters in the previously discussed comparisons and in the next chapter on system design option.

6.3 Recommendations

1) Based on the experimental field results, soil water content should be constant in the active root zone to alleviate salt hazards and minimize osmotic pressure impact on root water uptake.

2) Trickle irrigation under saline soil and water conditions should be designed with small spacing between emitters and lateral tubes to avoid salt accumulation midway between the emitters and lateral tubes at the soil surface.

3) Short irrigation intervals are more useful in avoiding crop yield reduction. Therefore, high irrigation frequency should be practiced under saline conditions.

4) Modeling trickle irrigation management for row crops under saline conditions can be an effective means of optimimzing trickle irrigation design and management strategies.

5) More research is recommended in the future using HYDRUS_2D model under different soil and water salinity conditions.

REFERENCES

Abu-Awwad, A. M. 1995. Salt distribution and soil water management for source trickle irrigated sweet corn. Dirasat (Pure and Applied Sciences). 22 (1): 7-20.

Abrol, I. P., J. S. P. Yadav and F. I. Massoud. 1988. Salt-affected soils and their management. Soils Bulletin, Paper No 39. FAO, Rome, Italy. 130 pp.

Allen, R. G. 1986. A Penman for all seasons. J. Irrig. and Drain. Engrg. ASCE.112 (4): 348-366.

American Public Health Association (Ed). 1995. Standards methods for examination of water and wastewater (19th Ed). American Public Health Association. Washington, DC. pp. 167-178.

Ayers, R. S. and D. W. Westcott. 1985. Water quality for agriculture. Irrigation and Drainage, Paper 29, Rev. 1. FAO, Rome, Italy. 96 pp.

Ayers, J. E., R. B. Hutmacher, R. A. Schoneman, S. S. Vail., S. H. Patton. and D. Felleke. 1985. Salt distribition under cotton trickle irrigation with saline water. In: ASAE. (Ed). Drip/Trickle Irrigation In Action, Proceedings of the Third International Drip/Trickle Irrigation Congress V II. ASAE, St. Joseph. MI. pp. 666-672.

Beltrao, J. and J. Ben-Asher. 1997. The effect of salinity on corn yield using the CERES-maize model. Irrigation and Drainage Systems 11: 15-28.

Black, C. A. 1968. Soil-Plant Relationships (2nd Ed). John Wiley and Sons, Inc New York, NY. 356 pp.

Braunworth, W. S., Jr. and H. J. Mack. 1989. Crop-water production functions for sweet corn. J. Amer. Soc. Hort. Sci. 114 (2): 2210-215.

Brooks, R. H. and A. T. Corey. 1966. Properties of porous media affecting fluid flow. J. Irrig. Drain. Div., ASCE. 72 (IR2): 61-88.

Bucks, D. A. and S. Davis. 1986. Trickle irrigation for crop production. Elsevier, Amsterdam. pp. 1-26.

Burman, R. D., P. R. Nixon, J. L. Wight and W. O. Pruit. 1983. Water requirement. In: M. E. Jensen (Ed). Design and Operation of Farm Irrigation Systems. ASAE Monograph. 189 pp.

Campbell, W. F., R. J. Wagenet and R. R. Rodriguez. 1986. Salinity, water management and fertility intractions on yield and nitrogen fixation in snap-beans. Irrig. Sci. 7: 195-204.

Cardon, G. E. and J. Letey. 1992. Plant water uptake terms evaluated for soil water and solute movement models. Sci. Soc. Am. J. 32: 1876-1880.

Coelho, F. E. and D. Or. 1996. A parametric model for two-dimensional water uptake intensity by corn roots under drip irrigation. Soil Sci. Soc. Am. J. 60: 1039-1049.

Cuenca, R. H. 1989. Irrigation system design: an engineering approach. Prentice Hall, Englewood Cliffs, NJ. Pp.154-173.

Dasberg, S. and D. Or. 1999. Drip Irrigation. Springer-Verlag, NY. pp. 3-63.

Doorenbos, J. and A. H. Kassam. 1979. Yield response to water. Irrigation and Drainage, Paper No 33. FAO. Rome, Italy.

Doorenbos, J. and W. O. Pruitt. 1984. Crop water requirements. Irrigation and Drainage, Paper No 24. FAO, Rome, Italy.

El-Gindy, A. M., H. I. Emad, M. S. Mohammed, S. E. Ahmed, M. A. Mohammed, and A. I. Kamal. 1990. Improved on-farm irrigation system in Egypt. Development Research and Technological Planning Center. Cairo University, Egypt.

Ferrer-Alegre, F. and C. O. Stockle. 1999. A model for assessing crop response to salinity. Irrig. Sci. 19: 15-23.

Goldberg, D., B. Gornat, M. Shmueli, J. Ben-Asher and M. Rinot. 1971. Increasing the agricultural use of saline water means of trickle irrigation. Water Resources Bulletin 7 (4): 802-809.

Hanson, R. B. and E. W. Bendixen. 1995. Drip irrigation controls soil salinity under row crops. California Agriculture 49 (4): 19-23.

Heermann, D. F., D. L. Martin., R. D. Jackson and E. C. Sgegmann. 1990. Irrigation scheduling control and techniques. In: Irrigation of agriculture crop-agronomy Monograph No 30, ASA. CSSA-SSSA, Madiso, WI.

Hoffman, G. J., S. L. Rawlins, J. A. Oster, J. A. Jobes and S. D. Merril. 1979. Leaching requirement for salinity control: wheat, sorghum, and lettuce. Agricultural Water Management 2: 177-192.

Hoffman, G. J., R. S. Ayers, E. J. Doering and B. L. McNeal. 1983a. Salinity in irrigated agriculture. In: M. E. Jensen (Ed). Design and Operation of Farm Irrigation Systems. ASAE Monograph, ASAE, St. Joseph. MI. pp.145-182.

Hoffman, G. J., J. A. Jobes, and W. A. Alves. 1983. Response of tall fescue to irrigation water salinity, leaching fraction, and irrigation frequency. Agricultural Water Management 7: 439-456.

Hoffman, G. J. and M. Th. Van Genuchten. 1983. Soil properties and effect water use: water management for salinity control. In: H. M. Taylor et al. (Ed). Limitations to Efficient Water Use in Crop Production. Amer. Soc. Agron. Madison, WI. Pp. 73-85

Hoffman, G. J., M. C. Shannon and J. A. Jobes. 1985. Influence of rain on soil salinity and lettuce yield. In: ASAE. (Ed). Drip/Trickle Irrigation in Action. Proceeding of the Third International Drip/Trickle Irrigation Congress V II. ASAE, St. Joseph, MI. pp. 659-665.

Hoffman, G. J., J. D. Rhoades and J. Letey. 1990. Salinity management. In: G. J. Hoffman et al. (Ed). Management of Farm Irrigation Systems ASAE Monograph, ASAE, St. Joseph. MI. pp. 671-687.

Homaee, M. 1999. Root water uptake under non-uniform transient salinity and water stress. Unpublished PhD dissertation, Wageningen Agricultural University, Wageningen, The Netherlands.

Hutmacher, R. B., C. J. Phene, K. R Davis, S.S. Vail, T. A. Kerby, M. Peters, C. A. Howk, M. Keeley, D. A. Clark, D. Baliard and N. Huson. 1995. Evapotranspiration, fertilizer management for subsurface drip acala and pima cotton. In: F. R. Lamm (Ed). Microirrigation for a Changing World: Conserving Resources/Preserving The Environment, Proceedings Fifth International Microirrigation Congress, ASAE. Orlando, FL: pp 147-154.

Jury, W. A., W. R. Gardner and W. H. Gardner. 1991. Soil physics (5th Ed). John Wiley and Sons, New York, NY. pp. 218-221.

Keller, J. and D. R. Bliesner.1990. Sprinkler and trickle irrigation. Van Nostrand reinhold. pp. 465-467.

Kruse, E. G. 1990. Salinity management options. In: K. K. Tanji (Ed). Agricultural Salinity Assessment and Management ASCE, Manuals and Reports of Engineering Practice No 71. ASCE, New York, NY. pp. 350-370.

Loague, K. and R. E. Green. 1991. Statistical and graphical methods for evaluating solute transport models: overview and application. Journal of Contaminant Hydrology 7: 51-73.

Maas, E.V. and G. J. Hoffman.1977. Crop salt tolerance current assessment. Journal of Irrigation and Drainage. ASCE. 103: 115-134.

Maas, E. V., G. J. Hoffman, G. D. Chaba, J.A. Poss and M. C. Shannon. 1983. Salt sensitivity of corn at various growth stages. Irrig. Sci. 4: 45-57.

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resources Res. 12 (3): 513-522.

Nightingale, H. I., S. J. Phene and S. H. Patton. 1985. Trickle irrigation effects on soil chemical properties. In: ASAE. (Ed). Drip/Trickle Irrigation in Action. Proceeding of the Third International Drip/Trickle Irrigation Congress V II. ASAE, St. Joseph, MI. pp. 730-735.

Nightingale, H. I., G. J. Hoffman, D. E. Rolsto and J. W. Biggar. 1991. Trickle irrigation rates and soil salinity distribution in an almond orchard. Agricultural Water Management 19: 271-283.

Ott, R. L. 1992. An introduction to statistical methods and data Analysis, (4^{th} Ed). Doxbury Press. Belmont, CA. pp. 870-889.

Oron, G., Y. Demalach, L. Gillerman and I. David. 1995. Pear response to saline water application distribution under subsurface drip irrigation. In: F. R. Lamm (Ed). Microirrigation for a Changing World: Conserving Resources/Preserving The Environment, Proceedings Fifth International Microirrigation Congress. ASAE, Orlando, FL. pp. 97-102.

Oster, J. D. 1994. Irrigation with poor quality water. Agricultural Water Management 25: 271-297.

Pasternak, D., Y. Demalach and I. Borovic. 1985. Irrigation with brackish water under desert conditions II. The physiological and yield response of corn (Zea mays) to continuous irrigation with brackish water and to alternating brackish-fresh-brackish water irrigation. Agricultural Water Management 10: 47-60.

Pasternak, D., M. Sagih, Y. Demalach, Y. Keren and A. Shaffer .1995. Irrigation with brackish water under desert conditions XI. Salt tolerance in sweet corn cultivars. Agricultural Water Management 28: 325-334.

Phene, C. J., R. B. Hutmacher, J. E. Ayers and J. Ben-Asher. 1995. Subsurface drip irrigation. In: F. R. Lamm (Ed). Microirrigation for a Changing World: Conserving Resources/Preserving The Environment, Proceedings Fifth International Microirrigation Congress. ASAE, Orlando, FL. pp.141-146.

Perroux, K. M. and I. White, 1988: Designs for disc permeameters. Soil Sci. Soc. Am. J. 52 (5): 1205-1215.

Pratly, J. and A. Robertson. 1998. Agriculture and the environmental imperative. Charles Sturt University, Australia. pp. 71-97.

Prendergast, J. B.1993. A model of crop yield response to irrigation water salinity: theory, testing and application. Irrigation Science 13: 157-164.

Ragheb, H. M., M. A. Gameh, M. H. Nafady and A. R. Ahmed. 2000. Growth, yield, water efficiency and nutrients contents of two bean varieties under trickle and sprinkler irrigation regimes in the new valley. Assiut Journal of Agricultural Science 31(2): 89-116.

Rhoades, J. D. 1974. Drainage for salinity control. In: J. Van Schilfgaarde (Ed). Drainage for Agriculture. Am. Soc. Agron. Monograph 17. pp. 433-461.

Rhoades, J. D. 1990. Overview: diagnosis of salinity problems and selection of control practices. In: K. K. Tanji (Ed). Agricultural Salinity Assessment and Management ASCE Manuals and Reports of Engineering Practice No 71. ASCE, New York, NY. pp. 18-41.

Rhoades, J. D., A. Kandiah and A. M. Mashali. 1992. The use of saline waters for crop production. Irrigation and Drainage, Paper No 48. FAO, Rome, Italy. 95 pp.

Russo, D. and D. Bakker. 1987. Crop-water production functions for sweet corn and cotton irrigated with saline waters. Soil Sci. Soc. Am. J. 51 (4): 1554-1562.

Sammis, T. W. and I. P. Wu. 1985. Effected of irrigation design and management on crop yield. Transaction of the ASAE, 28 (3): 832-837.

Shaiberg, I. and J. Shalhevet. 1984. Soil salinity under irrigation processess and management. Spring-Verlag, New York, NY. pp. 78-95.

Shalhevet, J., B. Heuer and A. Meiri. 1983. Irrigation intervals as a factor in the salt tolerance of eggplants. Irrig. Sci. 4: 83-93.

Shalhevet, J. and L. Bernstein. 1968. Effect of vertically heterogeneous soil salinity on plant growth and water. Soil Science 106 (6): 85-93.

Shalhevet, J., P. Reiniger and D. Shimshi. 1969. Peanut response to uniform and non-uniform soil salinity. Agronomy Journal 61: 384-387.

Simunek, J., T. Vogel and M. T. Van Genuchten. 1993. SWMS_2D: simulating water flow and solute transport in two-dimensional variably saturated media. U.S. Salinity Laboratory, USDA, ARS, Riverside, CA. 138 pp.

Simunek, J., T. Vogel and M. T. Van Genuchten. 1999. HYDRUS_2D: simulating water flow and solute transport in two-dimensional variably saturated media. U.S. Salinity Laboratory, USDA, ARS, Riverside, CA. 227 pp.

Singh, S. D., J. P. Gupta and P. Singh. 1978. Water economy and saline water use by drip irrigation. Agronomy Journal 70 : 948-951.

Soltanpour, P. N. 1985. Guide to fertilizer recommendations in Colorado. Cooperative Extension Service Colorado State University, Fort Collins, CO.

Szabolcs, I. 1989. Salt-affected soils. CRC Press, Inc. Boca Raton, FL. 274. pp.

Tanji, K. K. (Ed).1990. Nature and extent of agricultural salinity. In: K. K. Tanji (Ed). Agricultural Salinity Assessment and Management. ASCE Manuals and Reports of Engineering Practice No 71. ASCE, New York, NY. 619 PP.

Tscheschke, P., F. Alfaro, J. Keller and R. K. Hanks. 1974. Trickle irrigation soil water potential as incfluenced by management of highly saline water. Soil Sci. 117 (4): 226-231.

Van Genuchten, M. Th. 1980. A closed-form equation for predicting the hydraulic conductivity unsaturated soils. Soil. Sci. Am. Soc. J. 44: 892-898.

Vogel, T. and M. Cislerova. 1988. On the reliability of unsaturated hydraulic coductivity calculated from the moisture retention curve. Transport in Porous Media 3: 1-15.

Willmott, C. J.1982. Some comments on the evaluation of model performance. Bull. Am. Meteorol. Soc. 63 (11): 1309-1313.

Zhang, J., and R. L. Elliott.1996. Two-dimentional simulation of soil water movement and peanut water uptake under field conditions. Transaction of the ASAE. 39 (2): 497-504.

APPENDIX A

Table A.1. Average soil electrical conductivity, 1999.

Depth (cm)	Electrical conductivity dS/m											
	In the beginning of the season											
	T1		T2		T3		T4		T5		T6	
	0 cm	15 cm	0 cm	15 cm	0 cm	15 cm	0 cm	15 cm	0 cm	15 cm	0 cm	15 cm
0-30	3.32	3.42	3.287	3.49	3.39	3.39	3.18	3.18	3.20	3.20	3.30	3.30
30-60	3.54	3.54	3.291	3.70	3.59	3.59	3.53	3.53	3.59	3.59	3.69	3.69
60-90	3.77	3.77	3.679	3.71	3.70	3.70	3.51	3.51	3.64	3.64	3.63	3.63
	In the mid-season											
0-30	3.93	3.57	3.963	3.66	3.71	3.72	3.50	3.68	3.44	3.51	3.79	3.67
30-60	3.84	3.64	3.696	3.79	3.64	3.85	3.66	3.76	3.84	3.87	3.78	3.77
60-90	3.84	3.72	3.708	4.00	3.90	3.92	3.79	3.71	4.12	4.08	3.98	4.10
	In the end of season											
0-30	3.27	3.23	3.513	3.40	3.39	3.19	3.39	3.37	3.42	3.39	3.44	3.46
30-60	3.78	3.79	3.735	3.75	3.84	3.96	3.60	3.60	3.75	3.80	3.78	3.79
60-90	3.88	3.96	3.77	3.92	4.03	4.11	3.75	3.69	3.94	3.94	3.83	3.95

Table A.2. Average soil electrical conductivity, 2000.

Depth (cm)	Electrical conductivity dS/m											
	In the beginning of the season											
	T1		T2		T3		T4		T5		T6	
	0 (cm)	37.5 (cm)	0 (cm)	37.5 (cm)	0 (cm)	37.5 (cm)	0 (cm)	37.5 (cm)	0 (cm)	37.5 (cm)	0 (cm)	37.5 (cm)
0-15	4.41	4.41	4.29	4.29	5.18	5.18	4.26	4.26	4.50	4.50	5.26	5.26
15-30	4.50	4.50	4.91	4.91	5.48	5.48	4.84	4.84	4.59	4.59	5.44	5.44
30-45	4.76	4.76	4.99	4.99	5.64	5.64	4.74	4.74	5.34	5.34	5.96	5.96
45-60	4.83	4.83	5.22	5.22	5.81	5.81	5.22	5.22	5.69	5.69	6.17	6.17
60-75	5.56	5.56	5.82	5.82	5.92	5.92	5.04	5.04	5.57	5.57	5.90	5.90
75-90	5.14	5.14	5.11	5.11	5.90	5.90	4.75	4.75	5.41	5.41	6.17	6.17
	In the mid-season											
0-15	3.49	5.43	4.35	6.36	4.84	5.72	3.74	4.86	4.54	5.87	5.47	4.24
15-30	4.08	4.81	4.21	4.71	5.00	5.41	4.52	4.97	4.99	4.93	5.77	5.29
30-45	4.67	5.16	5.31	4.84	5.44	5.74	4.92	4.94	5.32	5.34	5.77	5.38
45-60	4.99	5.29	5.55	5.49	5.11	5.60	4.77	4.92	5.57	5.62	6.00	6.00
60-75	5.09	5.40	5.08	5.18	5.99	5.72	4.84	5.05	5.37	5.83	6.27	5.74
75-90	4.38	4.52	4.67	5.10	4.70	5.52	4.60	4.88	5.24	5.59	6.05	4.58
	In the end of season											
0-15	3.57	4.71	4.10	5.37	4.16	4.98	3.32	4.59	4.24	4.62	6.21	4.20
15-30	4.21	4.50	4.73	4.92	5.49	4.93	4.55	4.42	4.69	4.48	5.53	4.75
30-45	4.45	4.55	4.22	4.58	5.32	4.83	4.23	4.39	4.32	4.27	4.80	5.39
45-60	4.45	4.39	5.17	5.72	5.41	4.78	4.06	4.80	4.66	4.59	5.56	5.32
60-75	4.50	4.40	4.72	4.84	4.54	4.62	4.41	3.89	5.08	4.86	4.38	4.97
75-90	4.34	4.28	4.39	4.59	4.53	4.96	4.45	4.07	4.22	4.12	4.65	4.89

Table A.3. Simulated data of EC in the root zone, 1999.

Depth (cm)	Electrical conductivity dS/m At the end of the season											
	T1		T2		T3		T4		T5		T6	
	0 (cm)	15 (cm)	0 (cm)	15 (cm)	0 (cm)	15 (cm)	0 (cm)	15 (cm)	0 (cm)	15 (cm)	0 (cm)	15 (cm)
0-30	3.62	3.37	3.97	3.61	3.24	3.43	3.77	3.02	3.82	3.27	3.72	3.47
30-60	4.15	4.14	4.28	4.30	4.24	4.28	4.06	4.11	4.18	4.21	3.90	4.24
60-90	3.90	3.9	4.02	4.02	4.28	4.02	3.83	3.83	3.97	3.97	3.90	4.00

Table A.4. Simulated data of EC in the root zone, 2000.

Depths cm	Electrical conductivity dS/m At the end of the season											
	T1		T2		T3		T4		T5		T6	
	0 cm	37.5 cm	0 cm	37.5 cm	0 cm	37.5 cm	0 cm	37.5 cm	0 cm	37.5 cm	0 cm	37.5 cm
0-15	3.95	4.89	4.39	5.80	3.97	4.53	3.99	3.54	3.88	4.31	4.12	3.58
15-30	4.52	5.10	4.72	4.80	4.53	4.54	4.53	4.54	4.60	4.60	4.54	4.54
30-45	4.62	5.28	3.75	4.79	4.63	4.63	4.62	4.61	4.79	4.80	4.61	4.61
45-60	4.48	4.72	5.26	4.70	4.46	4.46	4.44	4.90	4.73	4.80	4.6	4.38
60-75	4.27	4.38	4.38	4.70	4.30	4.30	4.44	4.60	4.50	4.70	4.6	4.24
75-90	4.27	4.37	3.37	4.60	4.28	4.29	4.42	4.23	4.49	4.68	4.42	4.24

Table A.5. Comparison between simulated and observed salt accumulation to evaluate sensitivity of the model for different soil texture treatments irrigated every 7 days (100%ET).

Treatments	Depth	Simulation	Observation (Ece)	RMSE	RE	d
	cm	dS/m	dS/m		%	
Clay (field) 100%ET 0 cm	0-15	3.97	4.13	0.55	11	64
	15-30	4.53	5.07			
	30-45	4.63	5.11			
	45-60	4.46	5.03			
	60-75	4.30	4.97			
	75-90	4.28	4.90			
Clay (field) 100%ET 37.5 cm	0-15	4.53	5.19	0.67	12	35
	15-30	4.54	4.97			
	30-45	4.63	5.05			
	45-60	4.46	4.89			
	60-75	4.30	5.00			
	75-90	4.29	5.20			
Clay (model) 100%ET 0 cm	0-15	3.57	4.13	0.55	11.3	63
	15-30	4.56	5.07			
	30-45	4.64	5.11			
	45-60	4.47	5.03			
	60-75	4.37	4.97			
	75-90	4.31	4.90			
Clay (model) 100%ET 37.5 cm	0-15	3.7	5.19	0.80	15.9	20
	15-30	4.5	4.97			
	30-45	4.7	5.05			
	45-60	4.5	4.89			
	60-75	4.4	5.00			
	75-90	4.3	5.20			
Clay loam 100%ET 0 cm	0-15	5.39	4.13	0.67	13.8	11
	15-30	5.65	5.07			
	30-45	5.19	5.11			
	45-60	4.63	5.03			
	60-75	4.38	4.97			
	75-90	4.38	4.90			
Clay loam 100%ET 37.5 cm	0-15	5.5	5.19	0.53	10.56	50
	15-30	5.61	4.97			
	30-45	5.14	5.05			
	45-60	4.61	4.89			
	60-75	4.36	5.00			
	75-90	4.36	5.20			

Silt	0-15	5.32	4.13			
100%ET	15-30	5.77	5.07			
0 cm	30-45	5.23	5.11	0.67	13.7	15
	45-60	4.66	5.03			
	60-75	4.40	4.97			
	75-90	4.36	4.90			
Silt	0-15	6.12	5.19			
100%ET	15-30	5.63	4.97			
37.5 cm	30-45	5.10	5.05	0.65	13	12
	45-60	4.60	4.89			
	60-75	4.36	5.00			
	75-90	4.34	5.20			

A.6. Comparison between simulated and observed salt accumulation to evaluate sensitivity of the model for different soil texture treatments irrigated every 2 days (130%ET).

Treatments	Depth	Simulation	Observation (Ece)	RMSE	RE	d
	cm	dS/m	dS/m		%	
Clay (field)	0-15	3.99	3.65			
130%ET	15-30	4.53	4.54			
0 cm	30-45	4.62	4.75	0.35	6	71
	45-60	4.44	4.34			
	60-75	4.44	4.82			
	75-90	4.42	4.79			
	0-15	3.54	4.66			
Clay (field)	15-30	4.54	4.71			
130%ET	30-45	4.61	4.75	0.43	11	53
37.5 cm	45-60	4.90	5.01			
	60-75	4.60	4.65			
	75-90	4.23	4.85			
Clay	0-15	3.93	3.65			
(model)	15-30	4.54	4.54			
130%ET	30-45	4.64	4.75	0.35	7.8	65
0 cm	45-60	4.44	4.34			
	60-75	4.24	4.82			
	75-90	4.24	4.79			
	0-15	3.54	4.66			
Clay	15-30	4.56	4.71			
(model)	30-45	4.63	4.75	0.51	12	30
130%ET	45-60	4.37	5.01			
37.5 cm	60-75	4.24	4.65			
	75-90	4.24	4.85			

	0-15	4.39	3.65			
Clay loam	15-30	5.48	4.54			
130%ET	30-45	5.10	4.75	0.59	13.2	24
0 cm	45-60	4.52	4.34			
	60-75	4.30	4.82			
	75-90	4.30	4.79			
	0-15	5.38	4.66			
Clay loam	15-30	5.47	4.71			
130%ET	30-45	5.06	4.75	0.56	11.2	31
37.5 cm	45-60	4.49	5.01			
	60-75	4.30	4.65			
	75-90	4.30	4.85			
Silt	0-15	5.06	3.65			
130%ET	15-30	5.65	4.54			
0 cm	30-45	5.15	4.75	0.81	18.2	10
	45-60	4.58	4.34			
	60-75	4.29	4.82			
	75-90	4.29	4.79			
Silt	0-15	5.83	4.66			
130%ET	15-30	5.44	4.71			
37.5 cm	30-45	5.01	4.75	0.67	14	21
	45-60	4.50	5.01			
	60-75	4.29	4.65			
	75-90	4.29	4.85			

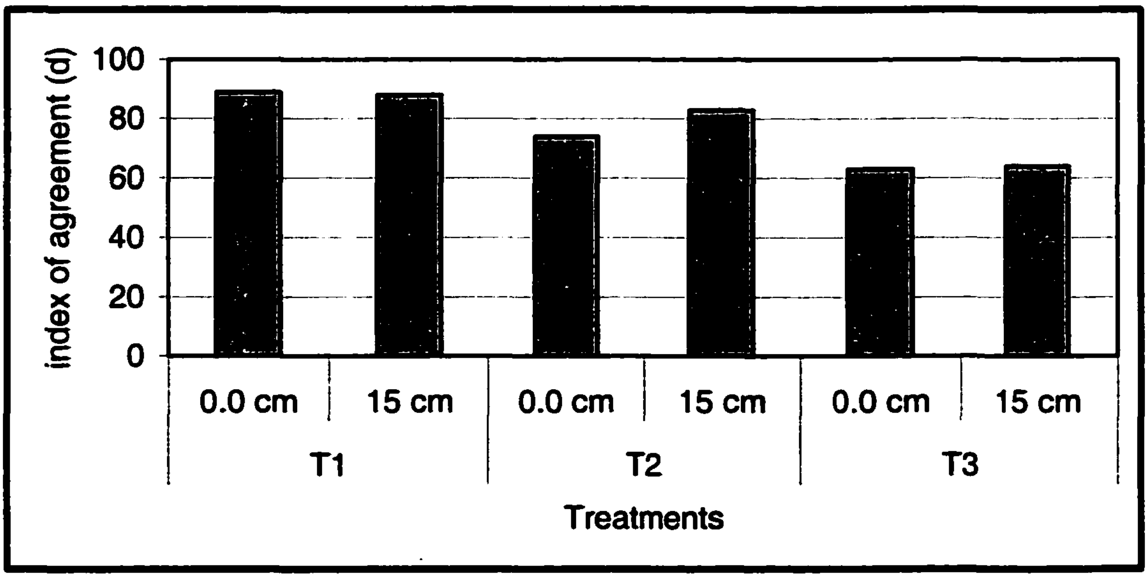

Figure A.1. Comparison of agreement between observed and simulated salt accumulation for 1999 season treatments irrigated every 7 days.

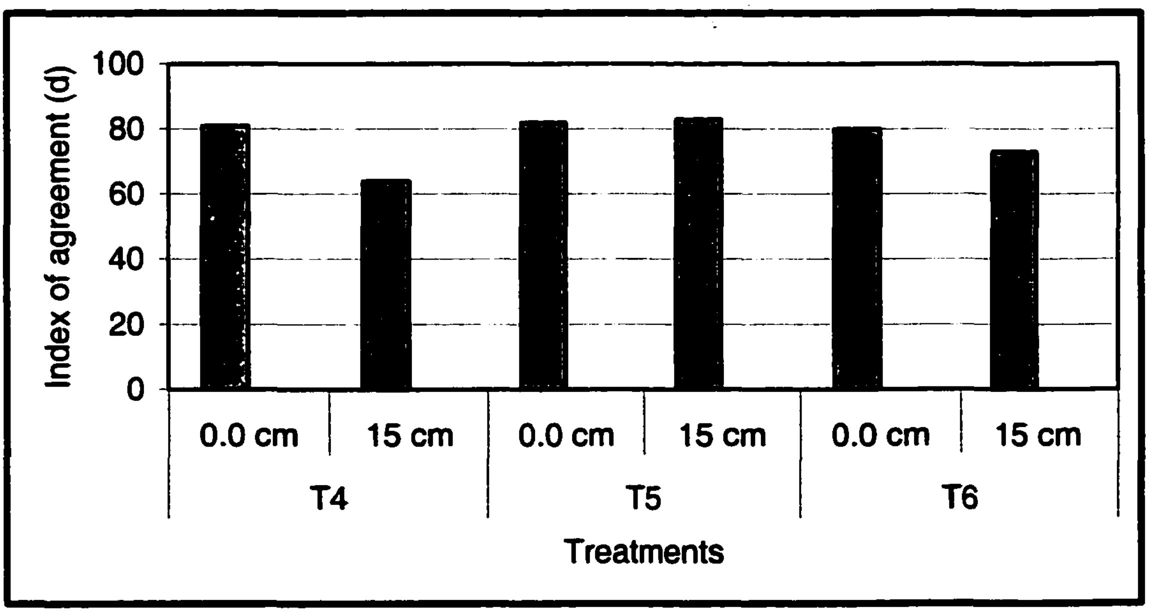

Figure A.2. Comparison of agreement between observed and simulated salt accumulation for 1999 season treatments irrigated every 3 days.

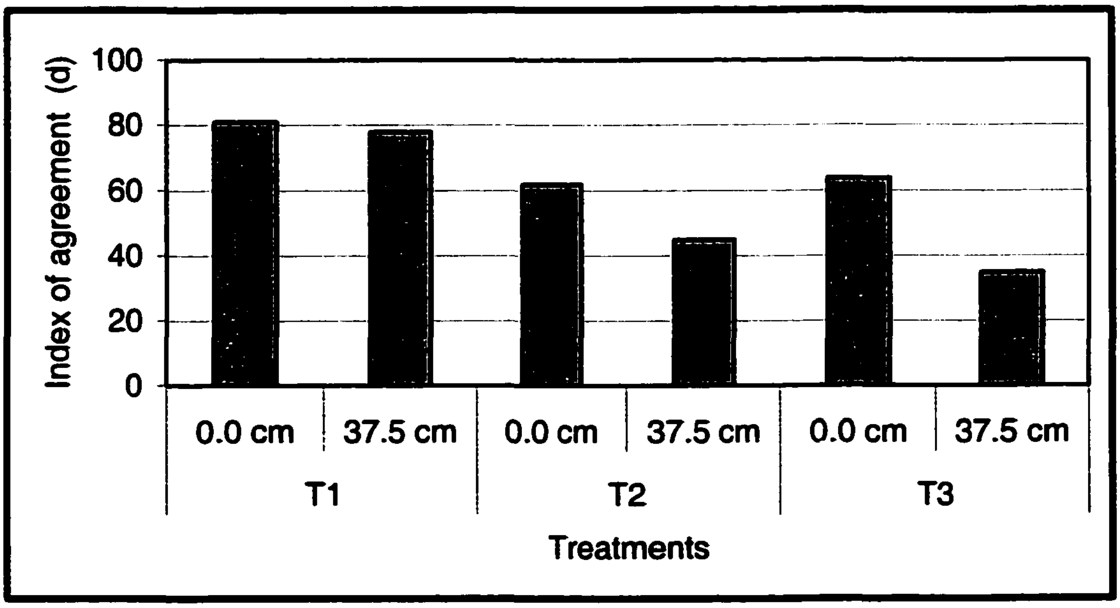

Figure A.3. Comparison of agreement between observed and simulated salt accumulation for 2000 season treatments irrigated every 7 days.

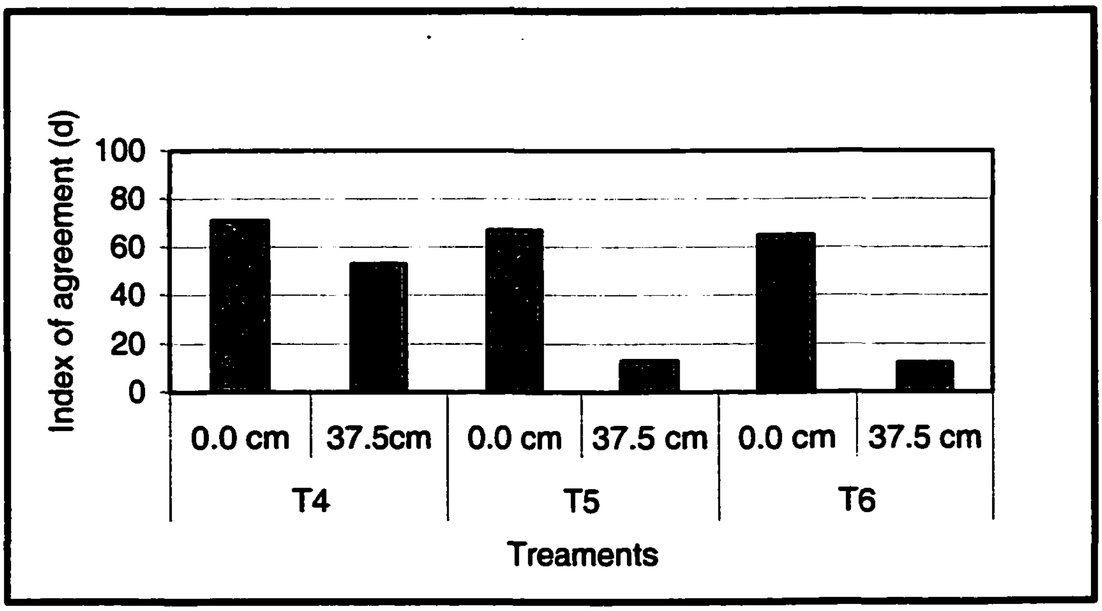

Figure A.4.Comparison of agreement between observed and simulated salt accumulation for 2000 season treatments irrigated every 2 days.

APPENDIX B

Table B.1. Cumulative transpiration; simulated by the model under every day irrigation interval.

Trteat. (%Etp)	App. (mm)	Emitters location of sample (cm)	Irr. intervals (days)	Tp (mm)	Ta (mm)	Ta/Tp	RY
85	261	15	1	158	158	1.00	1.00
85	261	30	1	157	156	0.99	0.99
85	261	40	1	157	153	0.98	0.97
85	261	45	1	157	153	0.97	0.96
85	261	70	1	157	149	0.95	0.94
85	261	100	1	158	141	0.90	0.87
100	307	15	1	158	158	1.00	1.00
100	307	30	1	157	156	0.99	0.99
100	307	40	1	157	154	0.98	0.97
100	307	45	1	157	153	0.97	0.97
100	307	70	1	157	149	0.95	0.94
100	307	100	1	158	140	0.89	0.86
115	353	15	1	158	158	1.00	1.00
115	353	30	1	157	156	0.99	0.99
115	353	40	1	157	154	0.98	0.97
115	353	45	1	157	153	0.97	0.97
115	353	70	1	157	149	0.95	0.94
115	353	100	1	158	140	0.89	0.86
120	368	15	1	158	158	1.00	1.00
120	368	30	1	157	156	0.99	0.99
120	368	40	1	157	154	0.98	0.97
120	368	45	1	157	153	0.97	0.97
120	368	70	1	157	149	0.95	0.94
120	368	100	1	158	140	0.89	0.86

Table B.2. Cumulative transpiration; simulated by the model under every 3 day irrigation interval.

Trt. (%Etp)	App. (mm)	Emitters location of sample (cm)	Irr. intervals (days)	Tp (mm)	Ta (mm)	Ta/Tp	RY
85	261	15	3	190	189	0.99	0.99
85	261	30	3	191	173	0.91	0.88
85	261	40	3	190	160	0.84	0.80
85	261	45	3	191	156	0.82	0.78
85	261	70	3	190	142	0.75	0.68
85	307	100	3	190	124	0.65	0.57
100	307	15	3	190	189	0.99	0.99
100	307	30	3	191	173	0.91	0.89
100	307	40	3	190	160	0.84	0.80
100	307	45	3	191	155	0.81	0.77
100	307	70	3	190	141	0.74	0.68
100	307	100	3	190	123	0.65	0.56
115	353	15	3	190	189	0.99	0.99
115	353	30	3	191	173	0.91	0.89
115	353	40	3	190	159	0.83	0.79
115	353	45	3	191	155	0.81	0.77
115	353	70	3	190	140	0.74	0.67
115	353	100	3	190	123	0.65	0.56
120	368	15	3	190	189	0.99	0.99
120	368	30	3	191	173	0.91	0.89
120	368	40	3	190	159	0.84	0.80
120	368	45	3	191	154	0.81	0.76
120	368	70	3	190	140	0.74	0.67
120	368	100	3	190	123	0.65	0.56

Table B.3. Cumulative transpiration; simulated by the model under 7 day irrigation interval.

Trt %ETp	App. (mm)	Emitters location of sample (cm)	Irr. intervals (days)	Tp (mm)	Ta (mm)	Ta/Tp	RY
85	261	15	7	193	190	0.99	0.98
85	261	30	7	193	173	0.89	0.87
85	261	40	7	193	160	0.83	0.79
85	261	45	7	193	157	0.81	0.77
85	261	70	7	192	147	0.77	0.71
85	261	100	7	193	133	0.69	0.61
100	307	15	7	193	190	0.99	0.98
100	307	30	7	170	158	0.93	0.91
100	307	40	7	193	160	0.83	0.79
100	307	45	7	193	158	0.82	0.77
100	307	70	7	194	146	0.75	0.69
100	307	100	7	193	131	0.68	0.60
115	353	15	7	193	190	0.99	0.98
115	353	30	7	170	158	0.93	0.91
115	353	40	7	170	149	0.88	0.85
115	353	45	7	194	157	0.81	0.76
115	353	70	7	194	145	0.74	0.68
115	353	100	7	193	131	0.68	0.60
120	368	15	7	193	190	0.99	0.98
120	368	30	7	170	158	0.93	0.91
120	368	40	7	170	152	0.89	0.87
120	368	45	7	193	157	0.81	0.77
120	368	70	7	192	146	0.76	0.70
120	368	100	7	194	131	0.68	0.60

Table B.4. Input data for the model as boundary conditions for 85%ET treatment at 15 cm location of sample between the emitters for every day irrigation interval.

Time of boundary condition change (days)	Precip. (cm)	Evap. (cm)	Transp. (cm)	Irr. water (cm)	EC (mmol) of Water
1	0	0.09	0.02	0.00	0
1.04	0	0.00	0.00	-0.15	32
2	0	0.04	0.01	0.00	0
2.04	0	0.00	0.00	-0.18	32
3	0	0.06	0.01	0.00	0
3.04	0.2	0.00	0.00	-0.12	32
4	0	0.08	0.02	0.00	0
4.04	0	0.00	0.00	-0.15	32
5	0	0.09	0.02	0.00	0
5.04	0	0.00	0.00	-0.17	32
6	0	0.10	0.02	0.00	0
6.04	0	0.00	0.00	-0.17	32
7	0	0.08	0.02	0.00	0
7.04	0	0.00	0.00	-0.15	32
8	0	0.10	0.02	0.00	0
8.04	0	0.00	0.00	-0.17	32
9	0	0.11	0.02	0.00	0
9.04	0	0.00	0.00	-0.20	32
10	0	0.12	0.02	0.00	0
10.04	0	0.00	0.00	-0.21	32
11	0	0.10	0.02	0.00	0
11.04	0.03	0.00	0.00	-0.16	32
12	0	0.09	0.02	0.00	0
12.04	0	0.00	0.00	-0.16	32
13	0	0.09	0.02	0.00	0
13.04	0	0.00	0.00	-0.16	32
14	0	0.10	0.02	0.00	0
14.04	0	0.00	0.00	-0.19	32
15	0	0.12	0.03	0.00	0
15.04	0	0.00	0.00	-0.18	32
16	0	0.10	0.02	0.00	0
16.04	0	0.00	0.00	-0.20	32
17	0	0.10	0.02	0.00	0
17.04	0	0.00	0.00	-0.26	32
18	0	0.11	0.02	0.00	0
18.04	0	0.00	0.00	-0.27	32
19	0	0.13	0.04	0.00	0
19.04	0	0.00	0.00	-0.26	32
20	0	0.14	0.05	0.00	0
20.04	0	0.00	0.00	-0.23	32
21	0	0.15	0.05	0.00	0
21.04	0.05	0.00	0.00	-0.28	32
22	0	0.11	0.04	0.00	0
22.04	0	0.00	0.00	-0.23	32
23	0	0.14	0.05	0.00	0
23.04	0	0.00	0.00	-0.30	32
24	0	0.13	0.09	0.00	0
24.04	0	0.00	0.00	-0.33	32
25	0	0.16	0.11	0.00	0
25.04	0	0.00	0.00	-0.40	32

26	0	0.16	0.11	0.00	0
26.04	0	0.00	0.00	-0.40	32
27	0	0.16	0.11	0.00	0
27.04	0	0.00	0.00	-0.40	32
28	0	0.18	0.12	0.00	0
28.04	0	0.00	0.00	-0.44	32
29	0	0.18	0.29	0.00	0
29.04	0	0.00	0.00	-0.70	32
30	0	0.16	0.26	0.00	0
30.04	0	0.00	0.00	-0.62	32
31	0	0.16	0.27	0.00	0
31.04	0	0.00	0.00	-0.64	32
32	0	0.13	0.21	0.00	0
32.04	0	0.00	0.00	-0.50	32
33	0	0.13	0.21	0.00	0
33.04	0	0.00	0.00	-0.50	32
34	0	0.1	0.41	0.00	0
34.04	0.1	0.00	0.00	-0.76	32
35	0	0.11	0.44	0.00	0
35.04	0	0.00	0.00	-0.82	32
36	0	0.12	0.48	0.00	0
36.04	0.46	0.00	0.00	-0.72	32
37	0	0.00	0.00	0.00	0
37.04	0	0.11	0.43	-0.74	32
38	0	0.00	0.00	0.00	0
38.04	0	0.08	0.34	-0.61	32
39	0.03	0.00	0.00	0.00	0
39.04	0	0.04	0.58	-0.78	32
40	0.25	0.00	0.00	0.00	0
40.04	0	0.04	0.48	-0.77	32
41	0	0.00	0.00	0.00	0
41.04	0	0.03	0.45	-0.73	32
42	0	0.00	0.00	0.00	0
42.04	0	0.04	0.56	0.00	32
43	0.58	0.00	0.00	-0.90	0
43.04	0	0.04	0.56	0.00	32
44	0	0.00	0.00	0.00	0
44.04	0	0.04	0.57	-0.56	32
45	0.8	0.00	0.00	0.00	0
45.04	0	0.04	0.5	0.02	32
46	0	0.00	0.00	0.00	0
46.04	0	0.03	0.42	-0.80	32
47	0.05	0.00	0.00	0.00	0
47.04	0	0.03	0.42	-0.64	32
48	0	0.00	0.00	0.00	0
48.04	0	0.03	0.43	-0.67	32
49	0.33	0.00	0.00	0.00	0
49.04	0	0.04	0.43	-0.50	32
50	0.33	0.00	0.00	0.00	0
50.04	0	0.03	0.33	-0.52	32
51	0	0.00	0.00	0.00	0
51.04	0	0.03	0.31	-0.54	32
52	0	0.00	0.00	0.00	0
52.04	0	0.05	0.5	-0.50	32
53	0	0.00	0.00	0.00	0
53.04	0	0.05	0.5	-0.81	32

54	0	0.00	0.00	0.00	0
54.04	0	0.05	0.46	-0.83	32
55	0.8	0.00	0.00	0.00	0
55.04	0	0.06	0.56	-0.76	32
56	0	0.00	0.00	0.00	0
56.04	0	0.05	0.48	-0.92	32
57	0.03	0.00	0.00	0.00	0
57.04	0	0.05	0.43	-0.78	32
58	0	0.00	0.00	0.00	0
58.04	0	0.05	0.47	-0.70	32
59	0	0.00	0.00	0.00	0
59.04	0	0.06	0.47	-0.77	32
60	0	0.00	0.00	0.00	0
60.04	0	0.06	0.43	-0.79	32
61	0	0.00	0.00	0.00	0
61.04	0	0.07	0.49	-0.72	32
62	0	0.00	0	0.00	0
62.04	0	0.06	0.42	-0.82	32
63	0	0.00	0.00	0.00	0
63.04	0	0.06	0.41	-0.71	32
64	0	0.00	0.00	0.00	0
64.04	0	0.08	0.32	-0.69	32
65	0	0.00	0.00	0.00	0
65.04	0	0.08	0.32	-0.59	32
66	0	0.00	0.00	0.00	0
66.04	0	0.09	0.35	-0.59	32
67	0	0.00	0.00	0.00	0
67.04	0	0.09	0.35	-0.65	32
68	0	0.00	0.00	0.00	0
68.04	0	0.09	0.37	-0.65	32
69	0	0.00	0.00	0.00	0
69.04	0	0.12	0.28	-0.70	32
70	0.03	0.00	0.00	0.00	0
70.04	0	0.1	0.24	-0.58	32
71	0	0.00	0.00	0.00	0
71.04	0	0.11	0.27	-0.51	32
72	0	0.00	0.00	0.00	0
72.04	0	0.1	0.24	-0.56	32
73	0.03	0.00	0.00	0.00	0
73.04	0	0.09	0.22	-0.51	32
74	0	0.00	0.00	0.00	0
74.04	0	0.12	0.12	-0.46	32
75	0	0.00	0.00	0.00	0
75.04	0	0.13	0.13	-0.37	32
76	0	0.00	0.00	0.00	0
76.04	0	0.12	0.12	-0.38	32
77	0	0.00	0.00	0.00	0
77.04	0	0.11	0.11	-0.37	32
78	0.97	0.00	0.00	0.00	0
78.04	0	0.11	0.11	-0.34	32
79	0	0.00	0.00	0.00	0
79.04	0	0.11	0.07	-0.33	32
80	0	0.12	0.08	0.00	0
82	0			-0.27	0

Table B.5. Input data for the model as boundary conditions for 85%ET treatment at 15 cm location of sample between the emitters for 3 day irrigation interval.

Time of boundary condition change (days)	Precip. (cm)	Evap. (cm)	Transp. (cm)	Irr. water (cm)	EC (mmol) of Water
1	0	0.09	0.02	0.00	0
2	0	0.04	0.01	0.00	0
3	0.2	0.06	0.01	0.00	0
3.01	0	0.00	0.00	-0.20	32
4	0	0.09	0.02	0.00	0
5	0	0.10	0.02	0.00	0
6	0	0.08	0.02	0.00	0
7	0	0.10	0.02	0.00	0
7.04	0	0.00	0.00	-0.63	32
8	0	0.11	0.02	0.00	0
9	0.03	0.12	0.02	0.00	0
10	0	0.10	0.02	0.00	0
11	0	0.09	0.02	0.00	0
11.04	0	0.00	0.00	-0.74	32
12	0	0.09	0.02	0.00	0
13	0	0.10	0.02	0.00	0
14	0	0.12	0.03	0.00	0
15	0	0.10	0.02	0.00	0
15.04	0	0.00	0.00	-0.73	32
16	0	0.10	0.02	0.00	0
17	0.05	0.11	0.02	0.00	0
18	0	0.13	0.04	0.00	0
19	0	0.14	0.05	0.00	0
19.05	0	0.00	0.00	-0.83	32
20	0	0.15	0.05	0.00	0
21	0	0.11	0.04	0.00	0
22	0	0.14	0.05	0.00	0
23	0	0.13	0.09	0	0
23.06	0	0.00	0.00	-1.04	32
24	0	0.16	0.11	0	0
25	0	0.16	0.11	0	0
26	0	0.16	0.11	0	0
27	0	0.18	0.12	0	0
27.09	0.1	0.00	0.00	-1.53	32
28	0	0.18	0.29	0.00	0
29	0.46	0.16	0.26	0.00	0
30	0	0.16	0.27	0.00	0
31	0.03	0.13	0.21	0.00	0
31.14	0.25	0.00	0.00	-2.40	32
32	0	0.13	0.21	0.00	0
33	0	0.10	0.41	0.00	0
34	0.58	0.11	0.44	0.00	0
35	0	0.12	0.48	0.00	0
35.15	0.8	0.00	0.00	-2.57	32
36	0	0.11	0.43	0.00	0
37	0.05	0.08	0.34	0.00	0
38	0	0.04	0.58	0.00	0
39	0.33	0.04	0.48	0.00	0
39.19	0.33	0.00	0.00	-2.74	32
40	0	0.03	0.45	0.00	0
41	0	0.04	0.56	0.00	0

42	0	0.04	0.56	0.00	0
43	0	0.04	0.57	0.00	0
43.18	0.8	0.00	0.00	-2.96	32
44	0	0.04	0.50	0.00	0
45	0.03	0.03	0.42	0.00	0
46	0	0.03	0.42	0.00	0
47	0	0.03	0.43	0.00	0
47.12	0	0.00	0.00	-2.08	32
48	0	0.04	0.43	0.00	0
49	0	0.03	0.33	0.00	0
50	0	0.03	0.31	0.00	0
51	0	0.05	0.50	0.00	0
51.12	0	0.00	0.00	-2.06	32
52	0	0.05	0.50	0.00	0
53	0	0.05	0.46	0.00	0
54	0	0.06	0.56	0.00	0
55	0	0.05	0.48	0.00	0
55.2	0.03	0.00	0.00	-3.32	32
56	0	0.05	0.43	0.00	0
57	0	0.05	0.47	0.00	0
58	0.03	0.06	0.47	0.00	0
59	0	0.06	0.43	0.00	0
59.18	0	0.00	0.00	-3.04	32
60	0	0.07	0.49	0.00	0
61	0	0.06	0.42	0.00	0
62		0.06	0.41	0.00	0
63	0	0.08	0.32	0.00	0
63.18	0	0.00	0.00	-2.94	32
64	0	0.08	0.32	0.00	0
65	0.97	0.09	0.35	0.00	0
66	0	0.09	0.35	0.00	0
67	00	0.09	0.37	0.00	0
67.15	0	0.00	0.00	-2.50	32
68	0	0.12	0.28	0.00	0
69	0	0.10	0.24	0.00	0
70	0	0.11	0.27	0.00	0
71	0	0.10	0.24	0.00	0
71.14	0	0.00	0.00	-2.36	32
72	0	0.09	0.22	0.00	0
73	0	0.12	0.12	0.00	0
74	0	0.13	0.13	0.00	0
75	0	0.12	0.12	0.00	0
75.1	0	0.00	0.00	-1.71	32
76	0	0.11	0.11	0.00	0
77	0	0.11	0.11	0.00	0
78	0	0.11	0.07	0.00	0
79	0	0.12	0.08	0.00	0
79.08	0	0.00	0.00	-0.7	32
80	0	0.12	0.08	0.00	0
81	0	0.11	0.07	0.00	0.0
81.04	00	0.00	0.00	-0.7	32
82	00	0.04	0.01	0.00	0

Table B.6. Input data for the model as boundary conditions for 85%ET treatment at 15 cm location of sample between the emitters for 7 day irrigation interval.

Time of boundary condition change (days)	Precip. (cm)	Evap. (cm)	Transp. (cm)	Irr. water (cm)	EC (mmol) of Water
1	0	0.09	0.02	0	0
2	0	0.04	0.01	0	0
3	0.2	0.06	0.01	0	0
4	0	0.08	0.02	0	0
5	0	0.09	0.02	0	0
6	0	0.1	0.02	0	0
7	0	0.08	0.02	0	0
7.04	0	0.00	0.00	-0.7	32
8	0	0.11	0.02	0	0
9	0	0.12	0.02	0	0
10	0.03	0.1	0.02	0	0
11	0	0.09	0.02	0	0
12	0	0.09	0.02	0	0
13	0	0.1	0.02	0	0
14	0	0.12	0.03	0	0
14.07	0	0.00	0.00	-1.2	32
15	0	0.1	0.02	0	0
16	0	0.11	0.02	0	0
17	0	0.13	0.04	0	0
18	0	0.14	0.05	0	0
19	0.05	0.15	0.05	0	0
20	0	0.11	0.04	0	0
21	0	0.14	0.05	0	0
21.09	0	0.00	0.00	-1.5	32
22	0	0.16	0.11	0	0
23	0	0.16	0.11	0	0
24	0	0.16	0.11	0	0
25	0	0.18	0.12	0	0
26	0	0.18	0.29	0	0
27	0	0.16	0.26	0	0
28	0	0.16	0.27	0	0
28.14	0	0.00	0.00	-2.3	32
29	0	0.13	0.21	0	0
30	0.1	0.1	0.41	0	0
31	0	0.11	0.44	0	0
32	0.46	0.12	0.48	0	0
33	0	0.11	0.43	0	0
34	0.03	0.08	0.34	0	0
35	0.25	0.04	0.58	0	0
35.25	0	0.00	0.00	-4.2	32
36	0	0.03	0.45	0	0
37	0.58	0.04	0.56	0	0
38	0	0.04	0.56	0	0
39	0.8	0.04	0.57	0	0
40	0	0.04	0.5	0	0
41	0.05	0.03	0.42	0	0
42	0	0.03	0.42	0	0
42.31	0.33	0.00	0.00	-5.1	32
43	0.33	0.04	0.43	0	0
44	0	0.03	0.33	0	0
45	0	0.03	0.31	0	0

46	0	0.05	0.5	0	0
47	0	0.05	0.5	0	0
48	0.8	0.05	0.46	0	0
48.24	0	0.00	0.00	-4	32
49	0.03	0.05	0.48	0	0
50	0	0.06	0.56	0	0
51	0	0.05	0.47	0	0
52	0	0.06	0.47	0	0
53	0	0.06	0.43	0	0
54	0	0.07	0.49	0	0
55	0	0.06	0.42	0	0
55.29	0	0.00	0.00	-4.9	32
56	0	0.08	0.32	0	0
57	0	0.06	0.41	0	0
58	0	0.09	0.35	0	0
59	0	0.09	0.35	0	0
60	0	0.09	0.37	0	0
61	0.03	0.12	0.28	0	0
62	0	0.1	0.24	0	0
62.32	0	0.00	0.00	-5.3	32
63	0.03	0.1	0.24	0	0
64	0	0.11	0.27	0	0
65	0	0.12	0.12	0	0
66	0	0.12	0.24	0	0
67	0	0.13	0.23	0	0
68	0.97	0.11	0.24	0	0
69	0	0.11	0.25	0	0
69.27	0	0.00	0.00	-4.5	32
70	0	0.13	0.27	0	0
71	0	0.13	0.26	0	0
72	0	0.13	0.13	0	0
73	0	0.12	0.12	0	0
74	0	0.11	0.11	0	0
75	0	0.11	0.11	0	0
76	0	0.11	0.07	0	0
76.23	0	0.12	0.08	-3.9	32
77	0	0.13	0.09	0	0
78	0	0.13	0.09	0	0
79	0	0.13	0.09	0	0
80	0	0.13	0.09	0	0
81	0	0.13	0.09	0	0
81.05	0	0.00	0.00	-0.9	32
82	0	0.13	0.09	0	0

Table B.7. Example of output data for the model for one irrigated treatment.

```
                          Welcome to HYDRUS-2D

Program HYDRUS2
Date:   1. 1.    Time:   1:43:12
Time dependent boundary conditions
Vertical plane flow, V = L*L
Units: L = cm   , T = days , M = mmol

Time [T]                  Total     Sub-region number ...

      .0000                           1
Area     [V]             .384E+04   .384E+04
Volume   [V]             .140E+04   .140E+04
InFlow   [V/T]           .000E+00   .000E+00
hMean    [L]            -.100E+03     -100.0
ConcVol  [VM/L3] 1       .589E+05   .589E+05
cMean    [M/L3]  1       .420E+02   .420E+02

     1.0000                           1
Area     [V]             .384E+04   .384E+04
Volume   [V]             .140E+04   .140E+04
InFlow   [V/T]          -.302E+01  -.302E+01
hMean    [L]            -.107E+03     -107.0
ConcVol  [VM/L3] 1       .589E+05   .589E+05
cMean    [M/L3]  1       .421E+02   .421E+02
WatBalT  [V]            -.590E-01
WatBalR  [%]                1.974
CncBalT  [VM/L3] 1       .138E+01
CncBalR  [%]     1           .954

     2.0000                           1
Area     [V]             .384E+04   .384E+04
Volume   [V]             .140E+04   .140E+04
InFlow   [V/T]          -.368E+01  -.368E+01
hMean    [L]            -.116E+03     -116.4
ConcVol  [VM/L3] 1       .589E+05   .589E+05
cMean    [M/L3]  1       .422E+02   .422E+02
WatBalT  [V]            -.698E-01
WatBalR  [%]                1.054
CncBalT  [VM/L3] 1       .576E+01
CncBalR  [%]     1          1.713

     3.0000                           1
Area     [V]             .384E+04   .384E+04
Volume   [V]             .139E+04   .139E+04
InFlow   [V/T]          -.367E+01  -.367E+01
hMean    [L]            -.127E+03     -126.5
ConcVol  [VM/L3] 1       .588E+05   .588E+05
cMean    [M/L3]  1       .422E+02   .422E+02
WatBalT  [V]            -.701E-01
WatBalR  [%]                 .682
CncBalT  [VM/L3] 1       .136E+02
CncBalR  [%]     1          2.534
```

4.0000				1
Area	[V]		.384E+04	.384E+04
Volume	[V]		.140E+04	.140E+04
InFlow	[V/T]		-.366E+01	-.366E+01
hMean	[L]		-.118E+03	-118.0
ConcVol	[VM/L3]	1	.590E+05	.590E+05
cMean	[M/L3]	1	.423E+02	.423E+02
WatBalT	[V]		-.144E+01	
WatBalR	[%]		6.987	
CncBalT	[VM/L3]	1	-.274E+02	
CncBalR	[%]	1	4.649	

5.0000				1
Area	[V]		.384E+04	.384E+04
Volume	[V]		.139E+04	.139E+04
InFlow	[V/T]		-.275E+01	-.275E+01
hMean	[L]		-.125E+03	-125.3
ConcVol	[VM/L3]	1	.590E+05	.590E+05
cMean	[M/L3]	1	.423E+02	.423E+02
WatBalT	[V]		-.147E+01	
WatBalR	[%]		6.310	
CncBalT	[VM/L3]	1	-.195E+02	
CncBalR	[%]	1	2.737	

6.0000				1
Area	[V]		.384E+04	.384E+04
Volume	[V]		.140E+04	.140E+04
InFlow	[V/T]		-.319E+01	-.319E+01
hMean	[L]		-.119E+03	-118.5
ConcVol	[VM/L3]	1	.591E+05	.591E+05
cMean	[M/L3]	1	.424E+02	.424E+02
WatBalT	[V]		-.308E+01	
WatBalR	[%]		9.125	
CncBalT	[VM/L3]	1	-.598E+02	
CncBalR	[%]	1	7.591	

7.0000				1
Area	[V]		.384E+04	.384E+04
Volume	[V]		.139E+04	.139E+04
InFlow	[V/T]		-.316E+01	-.316E+01
hMean	[L]		-.127E+03	-126.9
ConcVol	[VM/L3]	1	.591E+05	.591E+05
cMean	[M/L3]	1	.425E+02	.425E+02
WatBalT	[V]		-.305E+01	
WatBalR	[%]		8.267	
CncBalT	[VM/L3]	1	-.459E+02	
CncBalR	[%]	1	5.012	

8.0000				1
Area	[V]		.384E+04	.384E+04
Volume	[V]		.139E+04	.139E+04
InFlow	[V/T]		-.545E+01	-.545E+01
hMean	[L]		-.144E+03	-144.3
ConcVol	[VM/L3]	1	.591E+05	.591E+05
cMean	[M/L3]	1	.427E+02	.427E+02
WatBalT	[V]		-.311E+01	
WatBalR	[%]		7.328	

CncBalT	[VM/L3]	1	-.276E+01	
CncBalR	[%]	1	.234	

9.0000				1
Area	[V]		.384E+04	.384E+04
Volume	[V]		.139E+04	.139E+04
InFlow	[V/T]		-.311E+01	-.311E+01
hMean	[L]		-.131E+03	-131.1
ConcVol	[VM/L3]	1	.593E+05	.593E+05
cMean	[M/L3]	1	.427E+02	.427E+02
WatBalT	[V]		-.395E+01	
WatBalR	[%]		7.551	
CncBalT	[VM/L3]	1	.155E+02	
CncBalR	[%]	1	1.205	