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CYCLIC IRRIGATION OF TURFGRASS USING A SHALLOW SALINE AQUIFER

by

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Bachelor of Science
University of Nevada Las Vegas
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A thesis submitted in partial fulfillment
of the requirements for the

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ABSTRACT

Cyclic Irrigation of Turfgrass Using a Shallow Saline Aquifer

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Utilization of poor quality waters in the urban landscape has the potential of saving large quantities of good quality water for higher priority uses. Bermudagrass in particular is well suited to be irrigated with poorer quality water. A two-year field study was conducted to determine the long-term effects of applying shallow saline aquifer water to two turfgrass sports fields. The water (0.69 – 3.4 dSm^{-1}) was applied using cyclic irrigation during peak demand months (May - Oct). Treatments consisted of cycling saline water through the existing irrigation systems. Saline substitution of fresh water was set at 1, 2, 3 and 4 times per 7 freshwater irrigation events. Irrigations were applied using an ET feedback system and imposing a leaching fraction of 0.15. Turf color and cover, canopy temperature, bulk soil conductivity, soil moisture, leaf water potential, tissue moisture content and stomatal conductance were monitored on a bimonthly basis

during the peak demand months. All plots except for control, were instrumented with tensiometers and salinity sensors. Soil samples (2430 total samples at the University and 1530 total samples at the high school site) were taken yearly from each plot in a 5 x 5 grid fashion and analyzed for soluble salts. Contour maps were developed using geostatistical techniques. Results for the end of the experimental period (May 1997 – May 1999) at the University site showed that the 0-75 cm depth weighted soil salinity (ECe) decreased or stayed nearly the same in the 1, 2 and 3 out of 7 saline substitution treatments and only slightly increased (4.5 to 4.6 dSm^{-1}) in the 4 out of 7 treatment from 1997 to 1999 whereas the control increased 0.5 dSm^{-1} to 3.8 dSm^{-1} suggesting that saline water application had little influence on the depth weighted profiles. Soil salinity at the high school site showed increases in 0-75 depth weighted ECe from 1997 to 1999 for all treatments, with the control having the highest value of 6.9 dSm^{-1} in May 1999. Initial soil salinity for all treatments were higher at the high school site relative to that at the University site indicating residual salts prior to the experiment. Increases in soil salinity were still below the soil salinity threshold of 6.9 dSm^{-1} for bermudagrass (Mass and Hoffman, 1977). Salinity sensors showed the cyclic nature of soil salinity when irrigated with saline water and the subsequent return to baseline levels after the recovery or saline off period. More negative matric potentials helped to fuel increases in salinity sensor values at the University site. Soil salinity was seen to increase above threshold limits early in peak summer months for all three depths in the 1 out of 7 treatment, the 40 cm depth in the 3 out of 7 treatment and the 10 and 25 cm depths in the 4 out of 7 treatment at the University site. The increase in soil salinity was partly due to deficit irrigation on the front edge of the ETo curve due to ET feedback being a week out of phase. 3-dimensional analysis at the University site showed that the 4 out of 7 treatment gave the largest water savings (~ 49 cm) with only small increases in soil salinity (0.1 dSm^{-1}) and no distinguishable effect on color rating (9.3) and cover percentages (99-100%). Canopy temperatures at the University site showed small increases (0.9 °C) in May 1999 as saline substitution rate increased indicating little effect on the turfgrass as salt load increased. Subtle increases in canopy temperature with time could indicate a trend towards increased plant stress leading to decline in turf quality. It was shown that bermudagrass could be grown under various substitution rates with only small effects on soil salinity, canopy temperature and color rating while leading to significant irrigation day and freshwater savings. By using the 4 out of 7 saline substitution treatment as much as $5800 dollars could be saved during peak demand months and could be as much as $11,000 when water prices reach $4.50/1000 gallons.

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GLOSSARY

Crop coefficient (Kc). A simple multiplicative adjustment factor used to adjust or convert ETo to actual turf ET (ETa).

Electrical conductivity saturation extract (ECe). Conductivity of electricity through an extract of soil. Commonly used to estimate the soluble salt content in solution.

Evapotranspiration. The combined processes by which water is transferred from the earth surface to the atmosphere; evaporation of liquid and transpiration from plants.

Gravimetric water content. Amount of water per gram of soil oven dried at 105 °C for 48 hours.

Kriging. A method based on the theory of regionalized variables for predicting without bias and minimum variance the spatial distribution of earth components, including soil properties.

Leaching fraction. Drainage volume divided by the irrigation volume plus precipitation volume or the fraction of infiltrated irrigation water that percolates below the root zone.

Leaching requirement. The smallest leaching fraction that maintains normal plant growth and development under a given set of conditions.

Matric Potential. The part of the total soil water potential that is due to the effects of the soil matrix. It may be defined as the energy per volume required to move from the reference state to the soil at the same elevation without adding solutes or changing pressure, temperature or allowing the soil above the point to exert a force.

Osmotic Potential. The part of the total soil water potential that is due to the presence of solutes in the soil water. It may be defined as the energy per volume required to move from the reference state to a solution identical in composition except for the addition of solutes.

Potential evapotranspiration. The rate at which water if available, would be removed from wet soils and plant surfaces expressed as the rate of latent heat transfer per unit area or an equivalent depth of water.

Saline soil. A nonsodic soil containing sufficient soluble salt to adversely affect the growth of most crop plants. The lower limit of saturation extract electrical conductivity of such soils is conventionally set at 4.0 dSm^{-1} (at 25 °C). Bermudagrass has a salinity threshold of approximately 6.9 dSm^{-1}.

Soil water potential. The energy per unit quantity of water required to transfer water from the reference state to the state existing within the soil environment.

Tissue moisture. Amount of water per gram fresh weight of plant tissue.

Transpiration. The rate of water loss from the plant through the formation of water vapor in living cells, which is regulated by physical and physiological processes.

Turf cover. Plant volume per unit area.

Turf cover. Plant density per unit area.

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CHAPTER I

INTRODUCTION

Continued population growth in the arid southwest, associated with limited water resources, has compelled water managers to look at all possible solutions to address this water supply-demand dilemma. The ability to continue further growth and development depends largely on the management of existing water resources. With this in mind all other water resources whether of good or poor quality should be incorporated into future water use-plans. As a means of freeing up good quality water for higher priority uses, wastewater should be given careful consideration as a possible irrigation source, as a large percentage of freshwater is used for the irrigation of urban landscapes, primarily turfgrass. As much as 70% of the fresh water used in the Las Vegas Valley is residential use and as much as 50% is used to irrigate lawns (Southern Nevada Water Authority, 2000). In southern Nevada the Las Vegas Valley Water District believes that the water supply is large enough to extend the growth of this thriving area until 2010 after which other sources of water will have to be secured (Las Vegas Valley Water District, 2001).

Many poorer quality waters could be utilized as alternative irrigation sources, if proper irrigation management is practiced. It is well documented that many crops can be irrigated with saline water (Ayers et al., 1985; Miles, 1977; Frenkel et al., 1975; Rhoades et al., 1983; Rhoades et al., 1989). The shallow saline aquifer existing beneath the Las Vegas Valley (EC ~ 0.69 – 3.4 dSm^{-1}) is one such resource that could be used. Dean et al in 1996 showed that irrigating large areas of turfgrass with poor quality water (EC ~ 6.0 dSm-1) was possible while still having acceptable turfgrass color and cover. Leskys et al (1999) showed that minimizing the LF led to water savings, favorable soil salinity and plant response when using saline water (~2.5 dSm^{-1}) if high irrigation uniformity was achieved. Estimates place the volume of this shallow system at 100,000 acre feet or more. Preliminary research showed that this shallow system could be used as an irrigation supplement but not as a sole source for irrigating turfgrass.

As the cost of water continues to increase in the desert southwest the use of poor quality water can lead to large dollar savings. The shallow saline system is considered nuisance water and at this point is free to anyone who wants to tap into the system. With water bills approaching $1 million dollars for some golf courses in the Las Vegas area superintendents would have some incentive to look at alternatives to freshwater irrigation, such as the shallow aquifer system. Schools and parks would be other candidates for using this system.

A field scale study was initiated to investigate the optimum substitution rates of shallow aquifer water for the irrigation of large turfgrass areas. A cyclic irrigation strategy similar to Rhoades et al. (1989) was used during peak demand months and the effects of using this shallow system on large-scale turf areas were monitored. Research plots were established at the University of Nevada, Las Vegas practice football field and Valley High School soccer field. The objectives of the research were 1) determine the maximum substitution rate of shallow aquifer water that could occur during peak demand months without a decline in turf quality and 2) monitor the water and salt balances, and the associated turfgrass response after a two year on/off period.

CHAPTER II

REVIEW OF RELATED LITERATURE

Soil and Salinity

The use of saline water for the purposes of irrigation depends on many factors; one of which is site assessment. Sites that are suitable for the use of saline water should be initially low in salts. Salt-affected soils occur naturally in arid and semi-arid regions where there is not enough precipitation to leach salts downward through the soil profile (Harivandi 1992). Saline water should be evaluated before use to minimize the addition of more salts or heavy metals to the soil. The most critical parameters needed to assess water quality are: 1) total salt content; 2) sodium hazard (permeability); 3) toxic ion levels; 4) bicarbonate and 5) pH (Harivandi 1988). A general method for measuring the total salt content within the soil is to measure the electrical conductivity (EC) usually in dSm^{-1}. Salts are known to negatively affect growth with each species having its own threshold value. Sodium hazard is also a very important criterion to measure as sodium can cause decreases in soil permeability. Excessive sodium accumulation in the soil can create dispersive soil conditions that will impede water transport through the soil profile (Jury et al. 1991). Rhoades (1975, 1982) suggested that since the effects of exchangeable Na swelling and dispersion are counteracted by high electrolyte concentration, the soil sodicity (permeability) hazard cannot be assessed independently of electrolyte concentration (salinity). Permeability is often correlated with SAR (sodium adsorption ratio). The calculation for SAR is (Richards 1954):

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\dfrac{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}}{2}}$$

where cation concentrations are reported in meq/l. Saline water is made up of many elements, some in small concentrations. Many plants including turfgrass species can encounter problems if toxic levels of these elements occur. Boron is one such element that can build-up to toxic levels. Boron is a required for healthy growth of higher plants. Critical levels reported in the literature are 0.15 µg/g to 0.75 µg/g (Barber 1995). Variation in the critical level may be due to crops and type of soil evaluated. The most common source of B in soils is from irrigation water that is pumped from wells with high B contents and, to a lesser extent, from very shallow water tables and soils naturally high in B (Francois 1979). Necrosis of leaf tips is the major symptom of increased Boron levels. Oertli et al. (1961) showed that by removing leaftips through regular mowing, harmful effects of Boron toxicity were negated. However, in woody ornamental plants such a strategy is not possible.

Since the irrigation water bicarbonate content can also affect soil permeability, it must be evaluated along with sodium, calcium and magnesium content of both the soil and water (Harivandi 1988). Bicarbonate ions may combine with calcium and/or magnesium and precipitate as calcium and/or magnesium carbonate. As these ions precipitate out of the soil solution the SAR of that solution increases.

Plant Response to Salinity

The long-term use of saline water will eventually have harmful effects on soil chemistry and plant growth. An increase in soil salinity is the number one cause for reducing crop yields in irrigated agriculture (Shalhevet 1994). However, for non-agronomic crops like turfgrass, yield is of less concern, as turf managers tend to rate the visual parameters such as color and canopy density as more important. Well-established turfgrass is a prime candidate for the substitution of saline water as an irrigation source, as the more sensitive germination, early seedling stage has already occurred, so the water can be applied throughout the entire year. Many studies have been done to show that the use of saline water on turfgrass is viable. Dudeck et al. (1983) observed that bermudagrass grown in soil with high salinity (~9.9 dSm^{-1}) decreased in top growth and increased root growth. The concurrent decrease in top growth and increase in root growth may allow bermudagrass to survive osmotic and nutritional stress during times of high salinity (Harivandi et al. 1992). An increase in soil salinity my cause a direct or indirect decline in stomatal conductance. This decline in conductance would cause a decrease in gas exchange and photosynthesis thus leading to a decrease in plant growth and yield. Ackerson and Younger (1975) showed that decrease in growth rate was the first visible sign in response to salinity. This is a common response by many plants once the salinity threshold for that species has been reached (Maas 1986).

Bowman (1987) showed that increasing salinity decreased both stomatal conductance and net CO_2 uptake of a marsh and inland C_4 nonhalophyte grass. He went on to show that water use efficiency decreased with increasing salinity for the inland population and remained the same for the marsh population. Thus, under saline conditions the inland population lost more water per carbon gained than did the marsh population.

It is important to determine that a plants response to salinity is not a specific ion effect. Dudeck et al. (1983) used only NaCl in solution to irrigate bermudagrass resulting in reduced top growth with increasing salinity. This response may be linked to increases in Na or Cl. To overcome this question irrigation solutions should contain a make-up of more than just one salt, such as CaCl and NaCl.

Leaf water potential and osmotic potential of different turfgrass cultivars have been shown to respond differently as salinity increases (Peacock and Dudeck, 1985a). Dean et al. (1996) showed that bermudagrass (*Cynodon dactylon* L. ' Numex Sahara') and tall fescue (*Festuca arundinacea* Schreb.'Monarch') could be grown under salt stress (6.0 dSm^{-1}) with acceptable turf quality if irrigations were applied frequently and a 0.15 leaching fraction imposed. Devitt et al. (1989) also showed that turfgrass could be irrigated with water high in soluble salts. Maas and Hoffman (1977) showed that when maintaining a high leaching fraction (0.5), tall fescue had a salt tolerance threshold of 3.9 dSm^{-1} in the saturation extract and a 5.3% decrease per dSm^{-1}.

Osmotic Response to Soil Salinity

The use of poor quality water forces better management practices to be imposed to minimize plant stress. When high salt levels are reached in the soil this increases the osmotic pressure of the soil solution, thus making water less available to the turfgrass (Harivandi 1988). This was also substantiated in a study by Bresler and Hoffman (1986) where soil salinity led to a reduction in water uptake. In order for plants to extract water under saline soil conditions the plant must lower its osmotic potential in the roots by the uptake of ions in the soil solution or produce organic solutes to maintain lower cellular water potentials than is found in the surrounding soil. Plants that are not able to employ ways of dealing with the saline environment will eventually dehydrate and die. Dean-Knox (1998) showed significantly lower osmotic potentials in bermudagrass and tall fescue when irrigated with saline water (~6.0 dSm^{-1}) compared with freshwater.

Turf Color / Cover and Salinity

Turfgrass color is largely dependent on tissue moisture and nutrients, primarily nitrogen, available to the plant. In work done by Dean et al. (1996) tall fescue maintained adequate turf color and turf cover if the I/ETo ratio was kept above 0.80 and 0.65 for bermudagrass. The effect of salt stress depends on the extent (i.e. duration and degree) of the salinity as well as the plant species. One study found that relative top growth of 3 different bermudagrass cultivars was unaffected when irrigated with water of salinity varying from 0.9 to 17.2 dSm^{-1} (Francois 1988). The effects of salinity on turfgrass quality have been investigated in numerous studies (Dean et al. 1996, Devitt et al. 1990, Dudeck et al. 1983, Francois 1988, Hayes et al. 1990, Leskys et al.1999). Many of these studies have shown that a wide range in irrigation salinity can be used on different species of turf with little or no effect on color and cover if proper water management and soil monitoring are employed.

Irrigation Management Strategies

Salinity Blending vs. Cyclic Irrigation

In order to irrigate with saline water over the long term, many factors such as climate, quality of water, soil conditions, water availability, management practices and type of crop need to be addressed (Grattan, 1994). Soil salinity needs to be monitored constantly to make sure that threshold levels are not reached. Adequate drainage systems are sometimes needed to remove excess water from the field when considering long-term usage of saline water (Bradford and Letey, 1992). Alternative irrigation methods were first proposed by Rhoades (1977). When only one source of poor-quality water is available for irrigation, crop production is limited by the extent to which rainfall can leach salts from the upper part of the profile and by how the irrigation water is managed (Grattan 1994). Blending and cyclic irrigation are two commonly practiced irrigation strategies (Grattan and Rhoades 1990). Blending is a technique where irrigation water is mixed either before or during irrigation events to dilute the water. Dinar and Letey (1986) performed a study to determine optimal ratios of saline water to nonsaline water and found that the technical and economic feasibility of mixing waters of different quality increases as the EC of the saline water decreases, crop tolerance to salinity increases, desired relative yield decreases, or the relative price of saline to nonsaline water decreases. Dean et al. (1997) employed this strategy when irrigating plots of bermudagrass and tall fescue. The practice of blending is usually adopted to increase the existing water supply. In some cases water is blended as a short-term fix to get rid of excess drainage water. Wichelns et al. (1988) reported that some growers in the San Joaquin Valley of California were forced to blend their drainage water with good quality irrigation water for over two decades, until a drainage outlet was finally available. Shalhevet (1984) discussed the two blending strategies of network dilution vs. soil dilution. Network dilution uses a facility that allows the waters to be blended in specific proportions within the conveyance system. In soil dilution, the soil acts as a natural medium for blending the water supplies. The different waters are alternated either within an irrigation event or between irrigations.

Cyclic irrigation is the use of good quality water during the sensitive germination stage and the use of poor quality water during the active growth stage or the cyclic on/off period during the entire year or just during peak water demand months. This cyclic use of "low" and "high" salinity waters prevents the soil from becoming excessively saline (Rhoades 1989). Rhoades (1977) proposed that nonsaline water be used for pre-plant and early irrigations of the salt-tolerant crop and all irrigations of the moderately salt-sensitive crop. After the salt-tolerant crop is grown, good quality water would be used to reclaim the upper portion of the soil profile. Subsequent irrigations with good quality water during the remainder of the year would move previously accumulated salts farther down the soil profile and, it is hoped, ahead of advancing roots. Many field scale projects have been done to show that the use of cyclic irrigation can allow waters of high salinity to be used (Ayars et al. 1986 a, b; Bradford and Letey, 1992; Grattan et al., 1987; Rhoades, 1989; Sharma and Rao 1998). Ayars et al. (1986 a, b) conducted a cyclic irrigation study using drip rather than surface irrigation methods. For three consecutive years saline drainage water ($EC_w = 8.0$ dSm^{-1}) was applied to cotton after seedlings were established. The subsequent wheat crop was irrigated with good quality water ($EC_w < 0.5$ dSm^{-1}). Sugar beets followed wheat and were irrigated again with saline water after seedlings were established. The researchers found that yields from plots irrigated with drainage water were no different from those irrigated with only good quality water. Grattan et al. (1987) went on to test the cyclic irrigation practice by using saline drainage water to directly irrigate moderately salt-sensitive crops after they reached a salt-tolerant growth stage. They found that saline drainage water (EC = 8.0 dSm^{-1} and 6 mg B/l) applied after first flower could be used to irrigate melons and processing tomatoes without reducing yield. It was also found that drainage water, which supplied 65% of the irrigation water requirements, did in fact improve fruit quality. These studies reinforce the point that irrigation water with an EC_w in excess of the EC_w-threshold reported by Ayers and Westcot (1985) can be used without reducing yields. The fact that the salt exposure does not occur during the entire season and the crop experiences salt accumulation during the salt-tolerant growth stage are a couple of reasons why crops are able to tolerate saline water that exceeds the EC_w-threshold. Periodic reclamation of the soil may be required to avoid salt buildup to growth-limiting levels (Grattan 1994). However, the amount of good quality water needed to periodically reclaim the soil must be taken into account for long-term water economy. Grattan goes on to say that any "good quality" water savings during prereclamation years may be lost during reclamation, particularly if soil B is a constituent that needs to be reduced in the soil profile. Sharma and Rao (1998) conducted an experiment that used saline drainage water of varying salinity levels (ECiw = 6.0, 9.0, 12.0 and 18.8 dSm^{-1}) for 7 years, irrigating wheat during the dry winter season while pearl-millet and sorghum were grown during the rainy season. On an average, the mean yield reduction in wheat yield at different ECiw was 4.2% at 6, 9.7% at 9, 16.3% at 12 and 22.2% at 18.8 dSm^{-1}. Pearl-millet and sorghum yields decreased significantly only when saline water of 12 dSm^{-1} or higher was applied to the previous wheat crop. The high salinity and sodicity of the drainage water increased the soil salinity and sodicity in the soil profile during the winter season. Sharma and Rao (1998) stated that these hazards were eliminated by the subsurface drainage during the ensuing monsoon periods.

In general, if water availability is unrestricted, the cyclic technique has many advantages over the blending method: 1) soil salinity can be lowered at certain times to allow more salt-sensitive crops to be included in the rotation; 2) a water blending facility is not required; 3) the use of saline water supply can be maximized; and 4) water of higher salinities can be used (Grattan and Rhoades 1990).

The continued use of saline irrigation water with the cyclic method of management will depend on economic factors. Many turf managers have not made the switch to using poor quality water because there is still a freshwater supply being delivered at a reasonable price. Irrigation managers will be forced to use poor quality water only if good quality water is not accessible, becomes too expensive or if city/county governments mandate poor quality water usage for large areas of turf and urban landscapes.

Weather Station Feedback and Crop Coefficients

For managers of large turfgrass areas, proper irrigation management needs to employ the use of feedback information, such as the assessment of environmental demand. Microclimates can vary significantly across a golf course, and directly influence turf irrigation requirements (Jiang 1998). Weather station feedback is of great importance when determining the irrigation amounts. The key to optimizing the use of weather stations on large areas of turf is the selection of the appropriate crop coefficient (Kc)(Brown 1999). Crop coefficients can differ from tees, fairways and greens within a golf course so the availability of the appropriate Kc is required to tailor irrigation for each type of turf (Brown 1999). Devitt et al (1992) developed crop coefficients from studies where actual turf water use (ETa) was measured and compared with values of ETo computed from meteorological parameters. Proper estimates of evapotranspiration on a weekly basis can help achieve low leaching fractions (Devitt et al. 1983) which in turn minimizes the salt transport to underlying water and prevents salt build-up. Jensen (1975) indicated that low leaching requirements require a high uniformity of water application to avoid deficit irrigation on parts of the field receiving the least amount of water.

Leaching Fraction and Water Quality

When applying saline water to the field the irrigation manager must make certain that the crop is receiving enough water to meet ET and also keep salts from building up in the soil profile. Salt build-up in the root zone can eventually lead to increased osmotic stress, which decreases growth and can ultimately kill the plant. The application of too much water can lead to an increase in water tables and create even larger problems for the irrigation manger. A study in India by Boumans (1988) showed that to control salt load from irrigation drainage water, horizontal subsurface drains or shallow, vertical, skimming wells would be needed. Bradford and Letey (1992) simulated the effects of an increasing water table on cotton production. They found that under uniform irrigation conditions 1) higher yields were achieved by applying less irrigation during the crop season and more during the preirrigation for salt leaching purposes, 2) annual applied conditions 1) higher yields were achieved by applying less irrigation during the crop season and more during the preirrigation for salt leaching purposes, 2) annual applied water must equal evapotranspiration to avoid long term water table rise or depletion and 3) high cotton yields can be achieved for several years even if the water table is saline and no drainage occurs if the irrigation water is low in salinity.

Leaching fraction (LF) is defined as drainage volume divided by the irrigation plus precipitation volume or the fraction of infiltrated irrigation water that percolates below the root zone. The smallest leaching fraction that maintains normal plant growth and development under a given set of conditions is referred to as that site's leaching requirement (Harivandi 1992). The leaching requirement depends on the salinity of the irrigation water and the type of plant to be grown. Also, the soil type where the plant is grown influences water movement and ultimately the leaching. For example, 20 cm of rainfall passing through a sandy soil can remove approximately 50% of the salts in the top 90 cm. In a clay soil, 20 cm of water would reduce salts by 50% in only the top 45 cm (Oster et al. 1984). Shalhevet (1984) showed that intermittent leaching can be more effective at leaching salts through the soil instead of continuous leaching, i.e., after each irrigation.

Since crops respond, for the most part, to the average root zone salinity where most of the water extraction occurs (Hoffman 1990), relationships that predict average root zone salinity based on LF and salinity of the applied water are useful. The crop-water extraction pattern in the root zone influences this relationship. Rhoades (1982) proposed an extraction pattern of a plant that extracts 40, 30, 20 and 10% of available water from the upper to lower quarters of the root zone. This approach is reasonable since 90% of with root distribution. He went on to show that water uptake was usually greatest in the 0 to 5 cm soil region and the ability to predict water uptake based on root distribution and/or soil salinity would be poor and that great error might occur in using such an approach in predictive models.

Sprinkler systems provide an easy way to deliver irrigation water in a uniform manner. The uniform application not only ensures that the LF is being maintained over the field but also helps to move the salts uniformly downward. Light, frequent, sprinkler irrigations can cause soluble salts to build rapidly in the root zone. This practice can be dangerous in dry climates, where frequent light irrigations with water containing only moderate salt levels can result in salinity problems (Harivandi 1994). The upward movement of water carries salts to the surface where they may accumulate (Oster et al. 1984). However, high frequency, low volume irrigations based on ET feedback and an imposed 0.15 LF have been shown to maintain favorable salt profiles while minimizing oscillations in matric/osmotic stress (Dean et al. 1996; Devitt 1989; Devitt et al. 1990; Leskys et al. 1999).

CHAPTER III

METHODOLOGY

A two-year cyclic irrigation study was conducted at two sites located in the Las Vegas Valley. The first site was the practice football field (22555m^2) at the University of Nevada Las Vegas and the second site was the Valley High School soccer field (4500m^2). The site at the University had been planted with a hybrid bermudagrass, which was overseeded with a perennial rye grass. The high school study site had been planted with a common bermudagrass, which had not been overseeded with rye grass. However, during this two-year experiment a perennial ryegrass was overseeded each fall. The Soil Conservation Service (SCS) classified the soil at both the University and high school sites as a McCarran fine sandy loam. It is described as a coarse-loamy, mixed, thermic Typic Haplogypsid. $CaCO_3$ content can approach 30% and clay content averages less than 18%. It was apparent that the high school soccer field was placed on a modified McCarran where some amendments may have been added.

Prior to salinization a main irrigation delivery line was laid parallel to the existing main irrigation line at both sites to facilitate delivery of shallow aquifer water from a holding tank. The new lines were fitted with valves (Toro 252 Series 2") that were installed just beyond the existing valves. This allowed an operator to cycle fresh and saline water to the field and make use of the existing irrigation system in the field.

Backflow prevention devices were installed to ensure that no shallow aquifer water entered the freshwater supply line. The valves were connected to an irrigation timer.

During the installation of the delivery system, a shallow well was bored to tap into the perched shallow aquifer. The wells, approximately 100 feet deep delivered 35 GPM and filled a 10,000-gallon reservoir at the university site and 8 GPM and filled a 10,000-gallon reservoir at the high school. The tanks were equipped with an automatic shut off switch to prevent over filling if no irrigations were taking place. A 15 hp pump was installed to deliver saline water to the field. Once the parallel delivery system was completed an inspection of all irrigation heads in the research area was done. Heads that were improperly aligned were leveled and heads that did not rotate properly were removed and new Hunter I-40 heads were installed. After the heads were installed, uniformity tests were run by setting 25 catch cans in a 5 x 5 grid within each plot. Uniformities were calculated using the equation $CUC = 1 - (0.8s)/x$ (Hart and Reynolds, 1965), where s is the standard deviation and x is the mean. All plots had an imposed leaching fraction of 0.15 maintained by setting irrigation volumes using the following equation; $LF = (I * ETa)/ I$ where I is the irrigation volume based on pressure volume time curves obtained through uniformity measurements. ETa is an estimate of actual evapotranspiration obtained by multiplying potential ET (ETo) with a crop coefficient (Kc; Devitt et al. 1992).

An automated weather station (Weather Watch 2000, Campbell Scientific, Inc., Logan, UT) was set-up at both locations to monitor climatic variables. Rainfall, average hourly solar radiation, average wind direction and velocity, average temperature and average relative humidity were recorded on an hourly basis. An hourly potential evapotranspiration estimate (ET_o; modified Penman equation) was made using the hourly climatic data. Average daily ET estimates were used for the ET feedback to adjust irrigation volumes. New irrigation times were established using this method based on the previous 7 irrigation events.

Plots (replicated twice, 12.2 m x 12.2 m at the university and 6.1 m x 3.05 m at the high school) were established within irrigation zones to ensure no irrigation overlap. All plots were instrumented with salinity sensors and tensiometers at 10, 25 and 40 cm below ground level. The University plots were irrigated 1, 2, 3, or 4 times per 7 irrigation events with saline water (4 treatment plots plus a control plot, replicated twice totaling 10 plots). The high school plots were irrigated 1 or 2 times per 7 irrigation events with saline water (2 treatment plots replicated twice plus a control replicated twice totaling 6 plots). The fewer plots at the high school were dictated by the greater than four-fold lower flow rate from the well compared to the University site.

Throughout the study, the University field was mowed two times weekly at a height of 2.5 cm with a reel mower. The high school field was mowed on a weekly basis at a height of 3.0 cm with a flail mower. Clippings were allowed to remain on the field.

Prior to the first (May 15, 1997) and second salinization periods (May 15, 1998) and at the end of the experiment, soil samples were taken using a 4.5 cm diameter soil auger. Samples taken in 1997 were based on a 4 x 4 grid that was set-up within the plot at equidistant locations from the edges. Sampling in 1998 and 1999 was based on a 5x5 grid. All samples were collected at depths of 0-15 cm, 15-45 cm and 45-75 cm with an additional depth of 75-105 cm added in 1999. Additional soil samples were taken at depths of 105-135 cm, 135-165 cm and 165- 195 cm at the 2-2, 3-3 and 4-4 grid locations. Soil samples were dried and extracted using the saturation procedures outlined by the United States Salinity Laboratory (Handbook 60, 1954). Soil solutions extracted were analyzed for Na, K, Ca, Mg, CO_3, HCO_3, Cl, SO_4 and electrical conductivity; although, for this study only electrical conductivity will be discussed.

Bimonthly plant measurements were taken of canopy temperature (using an infrared thermometer, Everest Interscience, Tustin, CA), color/cover, water potential (Pressure bomb Model 3005, Soil Moisture, Santa Barbara, CA) and stomatal conductance (LI-1600 Steady State Porometer, LiCor, Inc., Lincoln, NE) and tissue moisture content (g H_2O/ g fresh tissue). Measurements were taken between 1130 to1300 hours. Soil parameters measured included soil moisture (Theta Probe type ML2x, Delta-T Devices, Cambridge, England), soil temperature (Digi-Sense Thermocouple thermometer, Cole-Parmer, Vernon Hills, IL) and bulk soil conductivity (EM 38, Geonics Inc., Mississauga, ON) during the growing season (May 15-Oct 15). The same measurements were taken during the off season (Oct 16- May 14) on a monthly basis except for stomatal conductance and water potential. Weekly salinity sensor readings (salinity bridge, Soil Moisture) and matric potentials (tensiometers, Soil Measurement Systems) were also taken. Salinity sensor and matric potential data were collected from January 1, 1997 to May 15, 1997 (representing the first off period) prior to the first salinization period. Daily meter readings were taken to monitor irrigation volumes at both sites and to evaluate volume - pressure - time relationships.

The monthly, weekly and annual end of season field measurements collected in a grid fashion were analyzed using geostatistical techniques (GS+3.1, Gamma Design Software, Plainwell, MI). Two-way ANOVAs were run on various data sets to determine if significant differences existed between treatments and between recovery periods in different years.

CHAPTER IV

ASSESSING INITIAL FIELD CONDITIONS

Irrigation System

Sprinkler System

Prior to initiation of the experiment (May 15, 1997) a parallel delivery system was installed to deliver the shallow saline groundwater at both sites. Both delivery systems were evaluated by pressurizing the lines and inspecting for leaks. The irrigation pipe was then buried following University landscape procedures as well as Clark County irrigation procedures. Control valves in the irrigation system were then linked to an irrigation control clock. Each research plot was then inspected for proper sprinkler head rotation and sprinklers replaced if needed, with Hunter I-40s at the University site and Rain Bird impact heads at the high school site.

Time/volume irrigation runs were done on all treatment plots to establish precipitation rates. Based on these precipitation rates a gallon amount was targeted and this amount was delivered to the field based on irrigation estimates. Because the pressures often varied and small changes in pressure led to large changes in gallons delivered, irrigation amounts were based on total gallons rather than on pressure-time curves.

Irrigation uniformity distributions were assessed prior to irrigating with saline water at both sites with adjustments made as needed to improve the system distribution. The average Christiansen Uniformity Coefficient (CUC) for all treatments at the University site was 0.81 with a standard deviation of 0.02 and 0.92 with a standard deviation of 0.01 at the high school site. For both sites, a coefficient of uniformity for near surface soil volumetric water content was assessed using a theta probe (gently forcing the steel waveguides into the soil until full contact was achieved, (0-10 cm depth increment). The average coefficient of uniformity (CU) for the near surface soil volumetric water content for all treatments at the University site was 0.85 with a standard deviation of 0.05. Soil conditions at the high school site did not allow the theta probe to be used for near surface measurements because of higher soil compaction in the near surface horizon.

Well Depths

Wells were drilled to depths of 30.5 m at the University and high school sites. However, the depth to the shallow groundwater system varied at both sites. A maximum depth to the water table at the University site was 5.5 m with a minimum depth to the water table of 4.5 m. A maximum depth to the water table at the high school site was 4.7 m with a minimum depth to the water table of 4.0 m (Fig. 1).

Well Yield

The well at the University site yielded 38.0 gallons per minute while the well at the high school site yielded only 8.0 gallons per minute. This lower yield at the high school site dictated that two fewer treatments be included in the experimental design compared to the University site.

Well Water Quality

Well water samples were taken every week during the peak demand months (May 15 – October 15). Water samples were measured for electrical conductivity (EC) and other cations and anions as dictated by the agreement with the Las Valley Water District (Table 1). EC values varied little at the University site with lowest conductivities of 3.3 dSm^{-1} in June of 1997 and highest conductivities of 3.4 dSm^{-1} in September of 1998 (Fig. 2). At the high school site EC values were at their lowest in June of 1997 with an EC of 0.9 dSm^{-1} and conductivities reached a high of 2.5 dSm^{-1} in September of 1997 (Fig. 2). For both seasons of substitution at the high school site a cycling up and down of the well water EC was observed. This cycling up at the beginning of the saline season and down at the end was possibly linked to increased turbulence from over pumping low yielding sediments and/or from up gradient lower quality waters forced down gradient associated with increased drainage during the active irrigation season.

Soil Parameters

Soil Salinity

Soil samples were taken prior to the first salinization At the University site initial soil salinity (ECe) for all treatments can be seen in Table 2. Salinity values ranged from a low of 3.2 dSm^{-1} for the control 45-75 cm depth increment to a high of 5.3 dSm^{-1} in the 45-75 cm depth increment for the 3 out of 7 saline irrigation substitution treatment. Some of the pre experiment ECe values for the University site were higher than the saline soil classification value of 4.0 dSm^{-1} but were well below the threshold value of 6.9 dSm^{-1} for bermudagrass. ECe values for the 0-15 cm depth at the high school site ranged from 3.6

dSm^{-1} in the 1 out of 7 saline treatment to 6.0 dSm^{-1} for the control. The control plot had an overall higher baseline soil salinity than the 1 and 2 out of 7 saline treatments (Table 3).

Salinity Sensors

At the University and high school site, salinity sensors were read 15 times prior to the initial salinization (OFF 1). Average salinity sensor values for the 10, 25 and 40 cm depths for all treatments at both sites are reported in Tables 4 and 5.

Bulk Soil Conductivity

Prior to the initial salinization, calibration work was conducted to determine whether soil salinity, gravimetric water content or an interaction of these parameters correlated with horizontally adjusted EM 38 measurements. At the University site gravimetric water content was more closely correlated with EM 38 readings than was soil salinity (r=0.84*** and r=0.36, ns). An interaction of both depth weighted gravimetric water content and soil salinity was also shown to be highly correlated with the EM 38 readings (r=0.86**).

At the high school site only soil salinity was correlated with the EM 38 measurements (r=0.83***). The calibration work showed that the EM 38 could be used to monitor bulk soil conductance and was therefore used as a feedback tool during the experiment. However, since the range in soil salinity was small from plot to plot, the EM 38 was a better predictor of soil water content than soil salinity. This is not to say that the EM 38 could not predict soil salinity, but that the range in soil salinity in this experiment was not high enough to develop a more useful working calibration curve.

Soil Moisture

Soil moisture (theta probe) measurements were not taken until well into the first year of salinization at both the University site and the high school site. Gravimetric water content for the University and high school sites was not calculated until the second soil sampling during May 1998.

Plant Parameters

Cover

Prior to the first salinization, the research plots at the University site had initial turfgrass cover ratings of 100%. This was compared to the high school site, which had cover percentages of 97%, 94% and 97% for the 0 (control), 1 and 2 saline irrigation substitution treatments.

Color ratings (refer to methodology chapter for rating scheme) for the University site were 8.9, 9.3, 8.8, 9.2 and 9.0 for the 0, 1, 2, 3 and 4 saline irrigation treatments. Statistical separation of these mean color ratings existed between the 0, 2 and 4 out of 7 saline irrigation substitution treatments and the 1 and 3 out of 7 saline irrigation substitution treatments. Although this statistical separation between treatments occurred, all of these ratings were viewed as excellent. Color ratings for the high school site were 8.3, 8.5 and 8.4 for the 0, 1 and 2 out of 7 saline treatments. No statistical difference was shown between these treatments. The lower color ratings at the high school site were a direct reflection of a lower maintenance turf management program being imposed (mineral fertilizer additions, irrigation deficits).

Tissue Moisture

At the University site average initial tissue moisture contents (April 1997) were 0.753, 0.718, 0.698, 0.730 and 0.742 for the 0, 1, 2, 3 and 4 saline irrigation substitution treatments respectively. Only the 2 out of 7 saline irrigation substitution treatment was statistically different from the control ($p<0.05$).

At the high school site average initial tissue moisture contents were 0.775, 0.647 and 0.682 for the 0, 1 and 2 out of 7 saline irrigation substitution treatments respectively. Both the 1 and 2 saline treatments showed a statistical separation from the control ($p<0.05$).

Canopy Temperature

At the University site initial canopy temperatures minus ambient temperatures (T canopy – T ambient) were 2.52, 3.46, 0.176, 2.32 and –0.26 for the 0, 1, 2, 3 and 4 out of 7 saline irrigation substitution treatments respectively. All treatments were statistically different from each other except for the 3 out of 7 treatment from control and 2 out of 7 treatment from the 4 out of 7 treatment ($p<0.05$).

At the high school site initial T canopy – T ambient were 1.25, 0.83 and –1.76 for the 0, 1 and 2 saline substitution treatments respectively. The 1 of 7 saline substitution treatment was statistically different from both the 2 of 7 saline substitution treatment and the control treatment ($p<0.05$).

Leaf Water Potential

At the University site average midday leaf water potentials in June of 1997 (first full month of data) were –0.79, -1.21, -1.04, -0.96 and –1.02 MPa for the 0, 1, 2, 3 and 4 saline irrigation substitution treatments respectively. No statistical separation between treatment means existed.

At the high school site average midday leaf water potentials (June 1997) were –1.68, -1.69 and –1.70 MPa for the 0, 1 and 2 saline irrigation substitution treatments respectively. No statistical separation between treatment means existed.

CHAPTER V

TEMPORAL RESPONSE

Soil Parameters

Soil Salinity (ECe)

Salinity levels after the first salinization and second salinization and recovery period at the University and high school sites are reported in Tables 6 and 7. Soil ECe values for all treatments on average increased with time for the 0-15 cm and the 15-45 cm depth increment. The 45-75 cm depth increment decreased with time for all treatments except for the control, which increased by 0.2 dSm^{-1}. When looking at the depth weighted 0-45 cm ECe values for all treatments showed an increase in soil salinity with time. Depth weighted 0-75 cm ECe values for all treatments declined or stayed the same except for the 4 out of 7 saline irrigation substitution treatments and control which increased by only 0.1 and 0.5 dSm^{-1} from 1997 to 1999 respectively.

Salinity Sensors

Salinity sensor values for the University and the high school sites cycled up and down during the experimental period (May 15, 1997 – May 15, 1999) although the high school site treatments were less amplified. All salinity sensor values by treatment, depth and site are shown in Figures 3 - 8.

Initial average salinity sensor measurements (based on 15 measurements prior to initial salinization) for the 1 saline irrigation substitution treatment at the University site were 7.52, 8.41 and 10.79 dSm^{-1} for the 10, 25 and 40 cm depths respectively (Fig. 3). After two years of application and recovery the average salinity sensor values for the last off period were 7.99, 8.30 and 8.64 dSm^{-1} for the 10, 25 and 40 cm depths respectively, suggesting little deviation from the original baseline values. During the first salinization period (May15, 1997 – Oct. 15, 1997) a high salinity sensor value of 20.83 dSm^{-1} was recorded (during the second year of salinization) the highest salinity sensor value of 23.42 dSm^{-1} was also recorded at the 40 cm depth. Although salinity values merged during the final off period of the experiment, revealing little salinity difference with depth, salinity increased with depth during the on-periods. The final average salinity values for the 1 out of 7 saline substitution treatment were still below the 6.9 dSm^{-1} ECe (~13.8 dSm^{-1} sensor value) threshold salinity value for bermudagrass (where sensor values are approximately twice the value associated with saturation extracts because of the relationship between field soil moisture content and saturation).

Initial average salinity sensor measurements for the 2 out of 7 saline irrigation substitution treatment at the University site were 4.71, 4.28 and 4.66 dSm^{-1} for the 10, 25 and 40 cm depth respectively (Fig. 4). After two years of application and recovery the average salinity sensor values for the last off period were 7.12, 6.30 and 6.61 dSm^{-1} for the 10, 25 and 40 cm depths respectively, reflecting a 30 to 35 % rise in the baseline salinity values. Salinity values showed no distinguishable trends with depth during either on or off periods. During the first salinization period a high salinity sensor value of 10.78 dSm^{-1} was recorded and during the second salinization season, no salinity sensor readings ever exceeded 10 dSm^{-1}. This treatment showed the least variation in soil salinity with only small oscillations in EC driven by the on/off periods. All of the salinity sensor values were below the salinity threshold of bermudagrass.

Initial average salinity sensor measurements for the 3 out of 7 saline irrigation substitution treatment at the University site were 4.65, 7.24 and 10.22 dSm^{-1} for the 10, 25 and 40 cm depths respectively (Fig. 5). After two years of application and recovery the average salinity sensor values for the last off period were 7.62, 8.31 and 9.00 dSm^{-1} for the 10, 25 and 40 cm depths respectively. Initial average salinity was highest in this treatment at the 40 cm depth then quickly moved lower only then to peak at 23.73 dSm^{-1} during the first salinization period. Average baseline salinity levels increased 39% at the 10 cm depth, whereas they increased 13% at the 25 cm depth and actually declined 12 % at the 40 cm depth. Although salinity values merged at the end of the final recovery period the overall trend was one of increasing salinity with depth. The return of the salinity to baseline during the last recovery kept the soil below the threshold value for bermudagrass at all three depths.

Initial average salinity sensor measurements for the 4 out of 7 saline irrigation substitution treatment at the University site were 4.13, 4.48 and 3.42 dSm^{-1} for the 10, 25 and 40 cm depths respectively (Fig. 6). After two years of application and recovery the average salinity sensor values for the last off period were 6.79, 7.52 and 6.90 dSm^{-1} for the 10, 25 and 40 cm depths respectively, reflecting a 39 to 50% rise in baseline salinity values. Salinity sensor values remained closely grouped through the first saline period. During the first recovery period some separation started to take place (higher values at shallower depths) with a tighter grouping after the second saline period.

Initial average salinity sensor values for the 1 out of 7 saline irrigation substitution treatment at the high school site were 2.17, 3.97 and 4.47 dSm^{-1} for the 10, 25 and 40 cm depths respectively (Fig. 7). After two years of application and recovery the average salinity sensor values for the last off period were 3.79, 4.64 and 5.82 dSm^{-1} for the 10, 25 and 40 cm depths respectively, reflecting a 14 to 50% rise in baseline salinity values.

Initial average salinity sensor values for the 2 out of 7 saline irrigation substitution treatment at the high school site were 7.15, 3.99 and 2.88 dSm^{-1} for the 10, 25 and 40 cm depths respectively (Fig. 8). After two years of application and recovery, the average salinity sensor values for the last off period were 5.31, 4.54 and 4.50 dSm^{-1} for the 10, 25 and 40 cm depths respectively, reflecting a minus 26 to a plus 36% rise in baseline salinity values.

Salinity Sensor Site Comparison

Prior to the initial salinization at the University site, the 1 and 3 saline irrigation substitution treatments had increasing salinity values weeks before the first application of saline water. This increase can be attributed to the deficit irrigation management that was taking place prior to the first on period. After initiation of the experiment, ET feedback was used to adjust irrigation events and help establish positive leaching.

The 1 out of 7 saline irrigation substitution treatment at the University site was on average, 5.2 dSm^{-1} higher for all depths when compared to the same treatment at the high school site. Both the University and the high school site exhibited cycling up and down of salinity levels, however, the University site salinity levels, on average, were 2.5 times higher during the first and second salinizations for the 1out of 7 saline substitution treatment and 1.5 times higher for the 2 out of 7 saline substitution treatment for all depths combined. The average values for the end of the last recovery period were 53, 44 and 32% higher at the University site for the 10, 25 and 40 cm depths respectively, showing large variation from site to site.

The 2 out of 7 saline irrigation substitution treatment salinity values were higher at the University site than the high school site. The conductivities were approximately 2 times higher for the 25 and 40 cm depths during the first saline period. Salinity levels for all depth at the University site increased with depth and followed the same trend throughout the experiment whereas the high school site showed decreasing salinity with depth. Salinity levels at the high school site were approximately 5.0 dSm^{-1} for the second saline period whereas the University site had average values of 7.5 dSm^{-1} for the same period.

Matric Potential

Matric potentials for the University and the high school sites cycled down and up (Figs. 9-14) during the experimental period (May 15, 1997 – May 15, 1999) although the treatments at the high school site were less amplified. Lowest matric potential values at all sites occurred during summer months when evaporative demand was highest.

The 1 out of 7 saline irrigation substitution treatment at the University site reached lows of –0.129, –0.132 and –0.124 MPa at the 10, 25 and 40 cm depths respectively, during the first on/off salinization period (Fig. 9). There was a dramatic decline in matric potentials at the beginning of the experiment at all three depths. Throughout the experiment the 25 and 40 cm depths responded in a more similar fashion, falling during the beginning of the on-periods and rising during the latter phases of the on-periods of salinization whereas the 10 cm depth responded quicker to soil moisture, with more frequent oscillations. These matric potential oscillations at all depths would suggest that this was an active zone for water uptake and/or redistribution.

The 2 out of 7 saline irrigation substitution treatment for the University site reached a low of –0.090 MPa at the 10 cm depth prior to the first salinization and reached below – 0.060 MPa five more times during the rest of the experiment suggesting greater influence of plant water uptake and/or redistribution (Fig. 10). After the first salinization the 25 and 40 cm depth stayed fairly constant throughout the experiment oscillating between – 0.009 and -0.042 MPa indicating that the ET feedback and irrigation frequencies were able to minimize the extent of soil drying.

The 3 out of 7 saline irrigation substitution treatment at the University site showed the same dramatic decrease in matric potential prior to imposing the ET feedback irrigations (Fig. 11). Matric potentials reached a low of –0.138 MPa for the 25 cm depth during the first salinization and –0.120 and –0.123 MPa for the 10 and 40 cm depth respectively. More favorable matric potentials were maintained from day 171 to the onset of the second salinization period at day 500, suggesting a 50-day lag in establishing soil moistures associated with the imposition of a 0.15 LF.

The 4 out of 7 saline irrigation substitution treatment at the University site showed very little decline in matric potentials until well into the first salinization period (Fig. 12). The 10 cm depth reached a low of –0.141 MPa during the first salinization and reached –0.107 MPa during the second salinization. Matric potentials reached lows of – 0.137 and –0.135 MPa for the 25 and 40 cm depth respectively. After day 550 matric potentials recovered to more favorable conditions, not falling below –0.020 MPa until day 783.

The 1 out of 7 saline irrigation substitution treatment at the high school site reached matric potentials of –0.089, -0.059 and –0.042 for the 10, 25 and 40 cm depths respectively, during the first salinization period (Fig. 13). Throughout the experiment all matric potentials for all three depths responded in a similar fashion, except during the first on/off salinization period. During the second salinization period matric potentials remained above –0.040 MPa for all three depths suggesting that ET feedback irrigations were producing more favorable soil moisture conditions.

Matric potentials for the 2 out of 7 saline irrigation substitution treatment at the high school site oscillated in a very similar sinusoidal fashion at all three depths with the 10 cm matric potential on average being the lowest (Fig. 14). During the first on/off salinization period matric potentials reached lows of –0.050 MPa at the 25 and 40 cm depths, with the 10 cm depth dipping below -0.060 MPa. Just prior to the second salinization period the 10 cm depth matric potential reached a low of –0.095 MPa. Midway through the second salinization period matric potentials dropped below –0.060 MPa. The 25 and 40 cm depth matric potentials remained above –0.020 MPa for most of the remainder of the second salinization period, suggesting that applied irrigations were able to minimize excessive soil drying.

Matric Potential Site Comparisons

For the 1 out of 7 saline irrigation substitution treatment a more noticeable response to irrigations was seen at the University site. The high school site had less dramatic oscillations as compared to the University site with the high school site showing a tighter response to irrigations during the second salinization period.

For both the University and high school sites the 2 out of 7 saline irrigation substitution treatment matric potentials showed tighter responses (less variation) to soil moisture at all depths than all other treatments. Matric potentials for both sites were highest during the second salinization period. Differences in matric potentials between sites with the same treatment may have been linked to growth differences in the turfgrass. We assumed that one Kc value could be used for both sites to adjust ETo values. However, growth and overall quality of the turfgrass was better at the University site. This possible error in the Kc value could have led to higher irrigations relative to ETa at the high school site, contributing to higher soil moisture and more positive matric potentials.

Salinity and Matric Potential Interactions

The 1 out of 7 saline irrigation substitution treatment at the University site had significant increases in soil salinity at the 10, 25 and 40 cm depth and decreasing matric potentials at the same depths suggesting that matric potentials fueled the increasing soil salinity. During the second on/off salinization period salinity sensors responded in a similar fashion to decreasing matric potentials. Both salinity sensors and matric potential returned to pre experiment values at the end of the two-year irrigation experiment.

The 2 out of 7 saline irrigation substitution treatment at the University site had a small rise in soil salinity during the first on/off salinization period and matric potentials decreased during this same time period. Very little change in soil salinity and matric potentials for all three depths was seen throughout the rest of the experiment, suggesting that irrigation management was working well in maintaining soil moisture while minimizing the concentration of salts.

The 3 out of 7 saline irrigation substitution treatment at the University site had significant increases in soil salinity during the first on/off salinization period, which corresponded to decreases in matric potentials. The second on/off salinization period had the same response but did not peak as high for the salinity or peak as low for matric potentials.

The 4 out of 7 saline irrigation substitution treatment at the University site showed small increases in soil salinity with small oscillations in matric potentials at all three depths prior to the first salinization period. During the first off period, separation between soil salinity at all depths was observed with the salinity decreasing with depth. Corresponding matric potentials were decreasing during the final phase of the first on period. During the second on/off salinization period both salinity sensors and matric potentials rose/declined in a similar fashion suggesting that increasing and decreasing of matric potentials was driving the cycling up and down soil salinity.

The 1 out of 7 saline irrigation substitution treatment at the high school site had very small oscillations in soil salinity while there were wide swings in matric potentials for all three depths during the first on/off salinization period. Small rises in soil salinity were observed during the remainder of the experiment and some increased cycling was observed in matric potentials for this same time period. On average, matric potentials did not decrease above –0.040 MPa and this would contribute to the small rise in soil salinity, as there was only a slight concentration effect.

The 2 out of 7 saline irrigation substitution treatment at the high school site responded in similar fashion to the 1 out of 7 treatment. At all three depths, salinity sensors showed small increases in soil salinity during the on periods and decreases during the off periods. Matric potentials oscillated throughout the experiment but on average stayed above the –0.040 MPa level at all three depths.

At both the University and high school sites, imposing feedback irrigations based on ET measurements from the week before would mean that there would be some deficit irrigations moving into the peak summer months and therefore causing an increase in soil salinity as matric potentials became more negative. The data would suggest that it might take approximately 50 days to get ahead of the ET curve to ensure irrigations were exceeding demand and this can be seen in the latter stages of the on periods for the 1 and 3 out of 7saline irrigations at the University site and both the 1 and 2 out of 7 saline irrigation treatments at the high school site.

Bulk Soil Conductivity

Average horizontally adjusted EM 38 values for the University site can be seen in Figure 15. EM 38 average values were highest for the 4 out of 7 saline irrigation substitution treatment during the second on/off salinization period while the control (0 of 7) had the lowest average values suggesting that the EM 38 could be used as a tool to monitor soil salinity. The 1, 2 and 3 saline irrigation substitution treatments responded in a similar fashion throughout the experiment suggesting that different application rates of saline water had little effect on soil salinity. At the University site there was a correlation between soil salinity (ECe) and EM 38 values (depth weighted ECe = 3.81 + 0.04 * horizontally adjusted EM 38 value, r = 0.64*). The EM 38 was also strongly correlated with depth weighted gravimetric water content (depth weighted gravimetric water = 0.008 + 0.006 * horizontally adjusted EM 38 value, r = 0.84***). This would suggest that the EM 38 was able to better record changes in soil moisture or an interaction between ECe and soil moisture (r = 0.86**).

At the high school site average horizontally adjusted EM 38 values were highest for the control (0 out of 7), while the 2 saline irrigation substitution treatment had the lowest average values (Fig. 16). ECe values for the control were higher than the 1 and 2 out of 7 saline irrigation substitution treatments throughout the experiment, which would support the higher readings by the EM 38. For the high school site a strong relationship existed between EM 38 values and depth weighted soil salinity (depth weighted soil salinity = 1.395 + 0.034 * horizontally adjusted EM 38 value, r = 0.83***), whereas no correlation was found between EM 38 values and depth weighted gravimetric water contents.

Site Comparison of Bulk Soil Conductivity

Average horizontally adjusted EM 38 values for the 1 out of 7 saline irrigation substitution treatment at the University were approximately 50% lower than the same treatment at the high school site throughout the experiment.

The 2 out of 7 saline irrigation substitution treatment at the University site was more than 2 times lower at the beginning of the experiment until the second on/off salinization period, when the high school site EM 38 values dropped to within 50 millisiemens. After the second on/off salinization period the University values continued to drop below 20 millisiemens whereas the high school site oscillated around 40 millisiemens. Since the EM38 measures bulk soil conductance, differences in soil texture, bulk density, soil fraction greater than 2mm, soil moisture and soil salinity can influence values. This would suggest a need for separate calibration curves for each site and an inability to infer a meaningful comparison based on raw data.

Soil Moisture (θ Probe)

Theta probe values measured at the near surface (0 – 8 cm) cycled up and down during the experimental period for all treatments at the University site (Fig. 17). During the first on/off salinization period the 2 saline irrigation substitution treatment had the lowest theta value (0.211). During the second on/off salinization period theta values for all treatments moved lower with the 4 out of 7 saline irrigation substitution treatment having the lowest value of 0.124. Theta values for all treatments continued to rise until the 580th day where they fell sharply until the end of the experiment.

Theta Probe (θ) and 10 cm Matric Potential Comparison

Comparison of the near surface theta probe values and 10 cm matric potentials for the 2 and 4 out of 7 saline irrigation substitution treatments at the University site showed similar temporal patterns (Fig. 18). During the first salinization period in the 2 of 7 treatment, when soil moisture content declined there was a sharp decline in matric potential. This was also evident during the second salinization when both the 2 and 4 of 7 treatments showed decreases in soil moisture and a corresponding decrease in matric potentials. However, even though similarities were present, based on 50 theta probe measurements and a single matric potential measurement it is hard to draw a meaningful conclusion based on the differences in sample size.

Plant Parameters

Temporal Response of Tissue Moisture Content

During the first off period tissue moisture content for all treatments at the University site continued to increase with the 3 out of 7 saline irrigation substitution treatment and the control reaching 0.78 g H_2O/g fresh weight. Shortly into the second salinization period all treatments declined suggesting that irrigations were out of phase moving into the peak demand months, however, average values for all treatments remained close to 0.70 g H_2O / g fresh weight. Midway through the second salinization, tissue moisture increased for all treatments until the end of the salinization period and then dropped sharply during the second off period. Tissue moisture contents during this period were as low as 0.44, 0.47, 0.61, 0.58 and 0.40 g H_2O / g fresh weight for the 1, 2, 3, 4, and control respectively (Fig. 19).

Tissue moisture during both salinization periods for the 1and 2 out of 7 saline irrigation substitution treatments and control at the high school site changed very little. Average tissue moisture contents during the first salinization were 0.64, 0.64 and 0.63 g H_2O / g fresh weight for the 1 and 2 out of 7 treatments and control respectively. During the second salinization period average values were 0.67, 0.66 and 0.64 g H_2O / g fresh weight for the 1 and 2 out of 7 treatments and control respectively. Even though control varied little during the on periods wide fluctuations were seen, ranging from 0.78 g H_2O / g fresh weight at the beginning of the experiment to 0.53 g H_2O / g fresh weight just prior to the second saline on period (Fig. 20).

Site Comparison of Tissue Moisture

Tissue moisture for the 1 and 2 out of 7 saline irrigation substitution treatments at both sites showed the same pattern of staying relatively constant during the salinization on periods and showing the wider oscillations during the salinization off periods. This suggests that irrigations at both sites, during the peak demand months were more frequent and in parallel with the environmental demand thus allowing the turfgrass to maintain a more positive water status. Also, at both sites the control plots showed the wider oscillations, at the University site this would suggest that irrigation managers were not as diligent in making sure that irrigations were taking place as needed. This was particularly true at the end of the second salinization when irrigations were cancelled and not made up.

Canopy Temperatures

Canopy Temperatures (T canopy – T ambient) at the University site for all treatments responded in similar fashion throughout the experiment (Fig. 21). During the salinization on-periods canopy temperatures were at their lowest while during the off- periods the temperatures were highest suggesting that transpiration and evaporative cooling were minimized during the winter months. Analysis of variance showed no separation between treatments during the on-periods (ns, $p=0.05$). On average, the control treatment showed the largest range (-5.3 to 12.2 °C) in canopy temperature, reflecting an irrigation management not as tightly based on an ET feedback approach.

Canopy Temperatures at the high school site for all treatments responded in a similar fashion throughout the experiment (Fig. 22). During the salinization on-periods canopy temperatures were at their lowest while during the off- periods the temperatures were highest suggesting that transpiration and evaporative cooling were minimized during the winter months. Analysis of variance showed no separation between treatments during the on-periods (ns, p=0.05). On average, the 2 saline substitution irrigation treatment showed the largest range (-6.6 to 14.8 °C) in canopy temperature.

Site Comparison of Canopy Temperature

Canopy temperatures at both the University and high school sites responded in similar fashion with the highest temperatures in the peak demand months and the lowest temperatures during the winter months (Oct. – May). For both the University and high school sites there was no separation between treatments indicating that increasing saline substitution rates had little effect on transpiration.

Midday Leaf Xylem Water Potential

Midday leaf water potentials at the University site showed a typical sinusoidal response to changes in season (Fig. 23). No statistical separation between treatments was seen (p=0.05, ns) during the on-periods for each successive year. The 1 out of 4 saline irrigation substitution treatment and control were statistically different from the first on period to the second on period ($p<0.05$). However, average values in leaf water potential decreased from the first salinization on-period to the second salinization on-period for all treatments, suggesting that irrigations during the second saline period were more in line with plant water requirements, allowing for a more positive plant water status.

Midday leaf water potentials at the high school site showed the same diurnal response as the University site (Fig. 24). Analysis of variance showed no statistical separation between treatments during the first and second on-periods ($p<0.05$). However, from the first to the second salinization on period all treatments showed statistical separation ($p<0.05$) as values declined during the second year.

Site Comparison of Midday Leaf Xylem Water Potential

Both the University and high school sites showed similar patterns in midday leaf water potential during the experimental period. Average leaf water potentials for both sites decreased during the second salinization on period, suggesting better irrigation management. The 1 and 2 saline irrigation substitution treatments at the University site showed lower average leaf water potentials than the same treatments at the high school site but no separation between treatments at either site occurred during the on-periods.

Turf Color

Color ratings for all treatments at the University site responded in a similar fashion throughout the experimental period (Fig. 25). Color ratings decreased just prior to the first salinization on period and then sharply increased within the first 60 days and on average, stayed above the 9.0 rating during the first on period. During the second salinization on-period average color ratings for all treatments were higher (9.3) and statistical analysis found no difference between treatments ($p<0.05$).

Color ratings for all treatments at the high school site cycled up and down during the experimental period (Fig. 26). Color ratings for the 1 and 2 saline irrigation substitution treatments reached lows of 7.35 and 7.54 respectively during the first salinization on-period. Control reached a low of 7.62 during the first off period. Color ratings for all treatments had no statistical difference ($p<0.05$) during each on period, however, statistical differences were seen as average color ratings from the first on period rose during the second on period for all treatments ($p<0.05$).

Site Comparison of Color Ratings

Similarities were seen between the University and high school sites in that, both showed the cycling up during the summer months when fertility was highest and cycling down during the winter months when the bermudagrass went into dormancy and winter rye was established. On average, colors rating for the 1 and 2 out of 7 saline irrigation substitution treatments at the University site were higher than the same treatments at the high school site possibly related to a residual nitrogen effect as the high school site had no prior nitrogen fertilization. Both sites showed overall increases in turf color ratings from the first saline period to second, indicating that this possibly correlated with improved irrigation management by year two.

Turf Cover

Average turfgrass cover percentages for the University site during the first salinization on period were all over 90 % with the 2 out of 7 saline irrigation substitution treatment having a cover percentage of 95 % (Fig. 27). After the first on period, cover percentages declined to below 80 % for all treatments and recovered during the second on-period. All treatments had average cover percentages of 100 % except for the 2 out of 7 treatment, which had a cover percentage of 97 %. During the first on period the 2 out of treatment was statistically different from all other treatments ($p<0.05$). Cover percentages during the second on period showed no statistical separation.

Average cover percentages at the high school site were all above 90 % during the first salinization on period. Cover percentages dropped sharply during the first off period and then recovered during the second on period (Fig. 28), indicating better growing conditions during the summer months and weaker establishment of the winter rye. All treatments increased in canopy density during the second year of saline water application, reflecting improved irrigation and nutrient management.

Site Comparison of Turf Cover

Throughout the experiment at both the University and high school sites turfgrass cover was maintained at excellent levels. The University had slightly higher percent turfgrass covers due to the higher degree of management from the University staff. The University site had a higher operation and maintenance budget as the field needed to be in good shape throughout the year because of continuous use.

CHAPTER VI

END OF STUDY FINDINGS

Actual vs. Imposed LFs

A leaching fraction of 0.15 was set at the beginning of the experiment for all treatments at both research sites. The control plot at the University site was maintained by the University staff, while our research team based on feedback from the landscape crew adjusted the control plot at the high school site. At the end of the experiment the LFs were evaluated based on the equation (Irrigation – ETa)/Irrigation for the entire experimental period. Where Irrigation is the total fresh and saline water applied to an experimental plot and ETa is an actual ET estimate obtained by multiplying the potential evapotranspiration rate (ETo) by a crop coefficient (Kc) for the same experimental period. Estimated end of experiment LFs at the University site based on this approach were 0.22, 0.22, 0.26, 0.24 and 0.30 for the 0 (control), 1, 2, 3, and 4 out of 7 saline irrigation substitution treatments respectively, and 0.30, 0.30, 0.34 for the 0, 1 and 2 out of 7 saline irrigation substitution treatments at the high school site.

Irrigation Treatments: Actual vs. Imposed

Treatments were set at 1, 2, 3 and 4 saline irrigation substitutions per 7 irrigation events for the University site and 1 and 2 saline irrigation substitutions per 7 at the high school site. Imposed ratios for each targeted treatment were 0.14 (1/7), 0.29 (2/7), 0.43 (3/7) and 0.57 (4/7) for the 1, 2, 3, and 4 saline irrigation substitution treatments. Actual ratios for the treatments at both sites varied slightly from the imposed values. Actual substitution ratios achieved were 0.16, 0.30, 0.46 and 0.57 for the 1, 2, 3 and 4 substitution rates at the University site and 0.16 and 0.28 for the 1 and 2 substitution rates at the high school site.

ETa vs ETo vs Irrigation

Irrigations were adjusted weekly using an ET feedback system, based on weather data input into the empirical Penmann Combination equation. The imposed LF was set at 0.15. Freshwater irrigation amounts incorporated rain events and this was factored into weekly irrigation changes. During irrigation peak demand months (May 15 – October 15) close attention was needed to make sure the ratios were upheld. Given this, there were still some irrigations that happened out of sequence. However, there was no real deviation from the ratios for the experimental period as a whole. ETo estimates were 2.6 m for all treatments for the entire experimental period for the University site and 2.8 m for both treatments at the high school site. ETa estimates based on incorporating published Kc values with ETo estimates for high fertility bermudagrass over seeded with ryegrass (Devitt et al, 1991) were 2.1 m for all treatments for the entire experimental period for the University site and 2.0 m for all treatments at the high school site. Actual irrigation (freshwater + saline water) amounts applied over the experimental period were 2.7 m, 2.7 m, 2.8 m, 2.7 m and 2.9 m for the 0, 1, 2, 3 and 4 saline irrigation substitution treatments at the University site. A comparison of ETa, ETo and monthly irrigation that was applied for the 4 out of 7 treatment at the University site is shown in figure 29. At the high school site actual irrigation amounts were 2.8 m, 2.8m and 3.0m for the 0, 1 and 2 saline irrigation substitution treatments.

Soil Parameters

Soil Salinity (ECe)

Soil salinity (ECe) at the University site for the 0-15 cm depth increment showed higher values in 1999 for the 0, 1, 2, 3 and 4 saline substitution treatments than 1997 (Table 6). Results for the 15-45 cm depth increment showed small changes in ECe values (~0.3 dSm^{-1}) for all treatments and the 45-75 cm depth showed a average decline in the 1, 2, 3 and 4 out of 7 saline substitution treatments (~0.6 dSm^{-1}) and an increase in the control treatment (~ 0.2 dSm^{-1}). On average, ECe values for all treatments for the 0-45 cm depth weighted ECe rose 0.5 dSm^{-1} from 1997 to 1999. Average values for the 0-75 cm depth weighted ECe declined 0.5 dSm^{-1} from 1997 to 1999 for the 1 and 3 out of 7 saline substitution treatments, remained the same for the 2 out of 7 treatment and increased an average of 0.3 dSm^{-1} for the 4 out of 7 treatment and control. At the end of the study all treatments were statistically different from the control ($p<0.05$) for the 0-15 cm depth increment. The 4 out of 7 showed statistical difference ($p<0.05$) from the control for the 15-45 cm depth increment from May 1999 and the 1 out of 7 treatment was statistically different from the control ($p<0.05$) for the 45-75 cm depth increment. Statistical separation was seen in both the 0-45 and 0-75 cm depth weighted ECes for all treatments when compared to control, even though the greatest change in ECe was only 0.9 and 0.7 dSm^{-1} respectively.

Normalized soil salinity (ECe) at the University site for all depths and treatments is listed in Table 8.

At the high school site average ECe values for all depth increments (0-15 cm, 15-45 cm and 45-75 cm) increased from 1997 to 1999 (Table 7). The 0-15 cm depth increment increased 1.6, 1.5 and 1.3 dSm^{-1} for the 1 and 2 out of 7 saline substitution treatments and control respectively. Both the 1 and 2 out of 7 treatments were statistically different from each other in 1997 and 1999 ($p<0.05$). The 1 and 2 out of 7 treatments were statistically different from control at the end of the study ($p<0.05$). The 15-45 cm depth increment increased 0.6, 1.3 and 1.3 dSm^{-1} for the 1 and 2 out of 7 treatments and control respectively, for the same time period. The 1 and 2 out of 7 treatments and control showed statistical separation from 1997 to 1999 and the 1 and 2 out of 7 treatments separated from control in 1999 ($p<0.05$). The 45-75 cm depth increment stayed the same for the 1 out of 7 treatment and increased 1.3 and 0.9 dSm^{-1} for the 2 out of 7 treatment and control respectively, from 1997 to 1999. Only the 2 out of 7 treatment showed statistical separation from 1997 to 1999 ($p<0.05$). Both the 0-45 cm and 0-75 cm depth weighted ECes increased with time and all treatments showed statistical difference from 1997 to 1999 ($p<0.05$). Though there was separation between the beginning and the end of the study for all treatments, salinity levels for all treatments were well below the salinity threshold for bermudagrass. The control treatment maintained the higher salinity levels throughout the experiment. Both the 1 and 2 out of 7 treatments were statistically lower than control for both the 0-45 cm and 0-75 cm depth weighted ECes at the end of the 2-year study ($p<0.05$).

Normalized soil salinity (ECe) at the high school site for all depths and treatments is listed in Table 9. Normalized data was calculated to account for pre-experimental conditions.

The number of soil samples needed at both the University and high school sites, to estimate the mean depth weighted soil salinity (ECe) within 10% at the 95% confidence level for each treatment were calculated and reported in Table 10. Sample numbers required at both the University and high school sites met the statistical requirement for all treatments at both the 0-15 and 0-75 cm depths.

Soil Salinity (ECe) Site Comparison

Soil salinity based on soil saturation analysis for both the University and high school sites showed overall increases at the 0-15 cm depth increment from 1997 to 1999 for the 1 and 2 out of 7 saline substitution treatments. The largest increase was seen at the high school site where the soil salinity increased 2.2 dSm^{-1} in the 1 out of 7 treatment. The 15-45 cm depth increment stayed the same for the 1 out of 7 treatment from 1997 to 1999 and decreased slightly 0.1 dSm^{-1} for the 2 out of 7 treatment from 1997 to 1999. The high school site showed a greater increase in soil salinity at the 15-45 cm depth. The 1 and 2 out of 7 treatments increased 1.6 and 1.9 dSm^{-1} respectively from 1997 to 1999. Soil salinity at the University site decreased 0.3 and 0.1 dSm^{-1} at the 45-75 cm depth from 1997 to 1999 for both the 1 and 2 out of 7 treatments respectively. Depth weighted 0-45 cm ECes at the University site, on average, rose 0.5 dSm^{-1} while ECes at the high school site, on average, rose 1.8 dSm^{-1} for both the 1 and 2 out of 7 treatments at both sites. Depth weighted soil salinity levels for the 0-45 cm increment at the University site were initially higher in both the 1 and 2 out of 7 treatments from the high school site but were lower in 1999 than the 0-45 cm increment for the 1 and 2 out of 7 treatments at the high school site, suggesting that the concentration effect at the University site was less because irrigation management was monitored more closely by the University staff. The 0-75 cm depth weighted ECe for the University site declined 0.3 dSm^{-1} in the 1 out of 7 treatment, stayed the same for the 2 out of 7 treatment and increased 0.5 dSm^{-1} for the control. This was in contrast to the 0.9, 1.5 and 1.1 dSm^{-1} increase seen in the 1 and 2 out of 7 treatments and control at the high school site.

Salinity Sensors

At the University site, average salinity sensor values increased for all treatments at the 10 cm depth from 1997 to 1999 (Table 4). Although after the two years of saline water application soil salinity at the 10 cm depth for both treatments was still below the bermudagrass salinity threshold. The 1 out of 7 saline substitution treatment was not statistically different from 1997 to 1999 whereas the 2, 3 and 4 out of 7 treatments were ($p<0.05$). At the 25 cm depth, salinity sensor readings in only the 1 out of 7 treatment decreased at the end of two years. The 2, 3 and 4 out of 7 treatments increased on average, 2.0 dSm^{-1} from 1997 to 1999. The 40 cm depth values declined 2.3 dSm^{-1} in the 1 out of 7 treatment, increased 2.0 dSm^{-1} in the 2 out of 7 treatment, declined 1.1 dSm^{-1} in the 3 out of 7 treatment and increased 3.4 dSm^{-1} in the 4 out of 7 treatment from 1997 to 1999. Analysis of variance showed the 40 cm depth increment for the 1, 2 and 4 out of 7 treatments were statistically different from 1997 to 1999 ($p<0.05$). However, these values were still below the bermudagrass salinity threshold.

Normalized salinity sensor values at the University site are listed in Table 11. Normalized data was calculated to account for existing baseline salinity from pre-experimental conditions.

Average salinity sensor values at the high school site for the 10 cm depth increased 1.1 dSm^{-1} for the 1 out of 7 saline substitution treatment and decreased 1.4 dSm^{-1} for the 2 out of 7 saline substitution treatment from 1997 to 1999 (Table 5). Analysis of variance showed statistical differences between treatments at the end of the study and differences in soil salinity from 1997 to 1999 ($p<0.05$). Average salinity sensor values for the 0-25 cm depth increased in both the 1 and 2 out of 7 treatments from 1997 to 1999. The increases were significant ($p<0.05$) but the final values were still well below the bermudagrass salinity threshold of 13.8 dSm^{-1}. Significant differences were found in the 1 and 2 out of 7 treatments from 1997 to 1999 and also between treatments within each year as the soil salinity rose over 1.0 dSm^{-1} for both treatments. This rise was small when looking at the overall salinity pattern and well below the salinity threshold for bermudagrass.

Normalized salinity sensor values at the high school site are listed in Table 12. Normalized data was calculated to account for existing baseline salinity from pre-experimental conditions.

Salinity Sensor Site Comparison

Initial average salinity sensor values for the 1 out of 7 saline substitution treatment at the University site were over 2 times higher than the high school site and were 3.0 dSm-1 higher, on average, in 1999 for all depths. The average salinity sensor values for the 2 out of 7 treatment at the University site were higher than the high school site at all three depths in 1997 and remained higher in 1999. On average, both the University and high school sites showed increasing salinity in both the 1 and 2 out of 7 treatments at all depths. These rises in salinity are an indication that concentration of salts within the soil solution were occuring in the first 40 cm which were due to a combination of salt loading and low leaching (0.15 LF imposed). However, because the salinity sensor values were taken from only one point within the treatment plots, greater weight must be given to the salinity analysis based on soil samples taken from the 5x5 grid pattern in each plot.

Matric Potential

At the University site, average matric potential values for the 10 and 25 cm depths for all treatments showed no statistical separation from 1997 to 1999 ($p<0.05$). Average matric potential values showed no statistical separation between treatments at all depths in 1999 after the two the year study ($p<0.05$). The 40 cm matric potentials in the 3 out of 7 saline substitution treatment showed statistical separation from 1997 to 1999 but did not separate out in 1999 from the other treatments.

At the high school site, average matric potential values for the 10, 25 and 40 cm depths in 1 and 2 out of 7 treatments showed no statistical separation between treatments in 1999 ($p<0.05$). The average matric potential for the 25 cm depth significantly increased ($p<0.05$) from 1997 to 1999 in the 2 out of 7 treatment. The average matric potential for the 40 cm depth for both the 1 and 2 out of 7 treatments showed a statistically significant increase from 1997 to 1999 ($p<0.05$).

Matric Potential Site Comparison

At the University site the 1 out of 7 treatment showed a decline in average matric potentials from 1997 to 1999 for all three depths, whereas, the high school site 1 out of 7 treatment showed an increase in matric potentials for the same time period. The 2 out of 7 treatment at the University site showed an increase at the 10 cm depth, a decrease at the 25 cm depth and no change at the 40 cm depth from 1997 to 1999. The high school site showed increases in matric potentials for all three depths in the 2 out of 7 treatment from 1997 to 1999. The high school site on average showed a greater increase in matric potential indicating dryer conditions within the soil at all depths in both treatments.

Bulk Soil Conductivity

At the University site, average bulk soil conductivity values were 28.1, 25.1, 20.5, 31.2 and 10.9 millisiemens for the 1, 2 3 and 4 out of 7 saline substitution treatments and control respectively, showing significant separation between all treatments ($p<0.05$) and control but no distinguishable pattern based on what we would expect for the differences in soil salinity. Data was analyzed with a backward stepwise regression comparing the effects of ECe and gravimetric water content on EM 38 values. Gravimetric water content accounted for 23 % of the variability in EM 38 values whereas ECe accounted for 57 % of the variability. Whereas, these two factors combined to account for approximately 80 % of the EM 38 variability.

At the high school site, average bulk soil conductivity values were 94.3, 88.8 and 120.2 millisiemens for the 1 and 2 out of 7 saline substitution treatments and control respectively. The 1 and 2 out of 7 treatments were statistically different from control and each other ($p<0.05$) but based on corresponding ECe data we would have expected the same separation in soil salinity, based on calibration curves, this was not the case.

Site Comparison of Bulk Soil Conductivity

EM 38 values at the high school site were over 200 % higher for both the 1 and 2 out of 7 treatments and the control was an order of magnitude higher than the same treatments at the University site. These significant increases in bulk soil conductivity were most likely due to other factors such as, soil bulk density, saturation content and /or greater than 2mm particle size fragments. Such results would suggest that calibration curves would have to be established for each site to be able to estimate the ECe based on EM 38 measurements.

Gravimetric Water Content

Gravimetric water content at the University site showed no distinguishable pattern of separation from treatment to treatment. The 2 and 3 out of 7 saline substitution treatments were the only treatments that separated from control ($p<0.05$). Gravimetric water contents for the 2 and 3 out of 7 treatments and control were 0.20, 0.14 and 0.17 respectively, indicating that treatment had no effect on determining gravimetric water content.

Gravimetric water content at the high school site, showed statistical separation between ($p<0.05$) the 1 out of 7 treatment and control and between the 1 and 2 out of 7 treatment. Average values were 0.246, 0.218 and 0.217 for the 1 and 2 out of 7 treatments and control respectively.

Site Comparison of Gravimetric Water Content

At the University site average gravimetric water contents for the 1 and 2 out of 7 saline substitution treatments and control were lower than the same treatments at the high school site. Even though there were differences between sites and treatments within each site, substitution rate had no distinguishable effect on gravimetric water content at either site.

Plant Parameters

Tissue Moisture Content

Average tissue moisture contents at the University site were 0.72, 0.75, 0.73, 0.76 and 0.77 g H_2O / g fresh weight for the 1, 2, 3 and 4 out of 7 saline substitution treatments and control respectively. Average tissue moisture increased as the saline substitution rate increased except for the 3 out of 7 treatment. The 1 and 3 out of 7 treatment were statistically different from the control ($p<0.05$).

Average tissue moisture contents at the high school site were 0.74,0.75 and 0.75 for the 1 and 2 out of 7 saline substitution treatments and control respectively. The 1 out of 7 treatment was statistically different from the control ($p<0.05$). Though there was statistical difference the tissue moisture contents were very similar, giving little meaning to the separation.

Site Comparison of Tissue Moisture Content

Tissue moisture contents for both the University and high school sites were similar at the end of the study with the control treatment at the University showing the highest value. Statistical separation was seen at both sites but no distinguishable pattern was evident.

Canopy Temperature

Average canopy temperatures (ambient temperature – canopy temperature) at the University site were 3.5, 4.2, 4.6, 4.4 and 6.1 °C for the 1, 2, 3 and 4 out of 7 saline substitution treatments and control respectively (Fig. 21). Canopy temperature for all treatments were significantly lower than the control plot ($p<0.05$). The 1 out of 7 treatment was also statistically different from the 3 and 4 out of 7 treatments ($p<0.05$).

Average canopy temperature for the high school site were 1.1, 3.2 and 3.0 °C for the 1 and 2 out of 7 saline substitution treatments and control respectively (Fig. 22). Statistical differences were seen between the 1 out of 7 treatment and the 2 out of 7 treatment and control ($p<0.05$), suggesting a mixed substitution rate effect on canopy temperature.

Site Comparison of Canopy Temperature

Canopy temperatures at both the University and high school sites varied from treatment to treatment with the University site showing the highest average canopy temperature. The university site had higher canopy temperatures on average, than the high school site for the 1 and 2 out of 7 treatments however, because the control plots had the highest temperatures, the significance of the treatment response is confounded.

Midday Leaf Xylem Water Potential

Water potential values at the University site (Fig. 23) were similar (-1.1 to –1.2 MPa) between treatments, with the control having the lowest value at –1.3 MPa. No statistical separation between treatments was observed, indicating that there was no effect of substitution treatment on midday leaf water potential.

Water potentials at the high school site (Fig. 24) were –1.4, -1.1 and –1.2 for the 1 and 2 out of 7 saline substitution treatments and control respectively. Analysis of variance showed that the 1 and 2 out of 7 treatments were statistically different ($p<0.05$). However, with the small difference in treatment values it would be difficult to draw meaningful conclusions as to whether substitution treatment had a meaningful effect on leaf xylem water potential.

Site Comparison of Midday Leaf Water Potential

Average leaf xylem water potentials for all three treatments were lower at the University site (-1.26 MPa) than for the same treatments at the high school site (-1.23 MPa). The differences between treatments and sites were small suggesting that salt-water induced stress, if present, had the little or no effect on the ability of bermudagrass to regulate leaf water potentials.

Turf Color

Average color ratings at the University site (Fig. 25) were above 9.5 (excellent) for all treatments with the 1 out of 7 saline substitution treatment having the highest value of 9.6. Statistical difference existed between the 1 out of 7 and the 3 out of 7 treatments ($p<0.05$). However, distinguishing between treatments with a visual rating difference of 0.1 has little applied meaning.

Average color ratings at the high school site (Fig. 26) were 9.5, 9.7 and 9.7 for the 1 and 2out of 7 treatments and the control respectively. The 1 out of 7 treatment was statistically lower than the 2 out of 7 and control ($p<0.05$) however, the rating difference was small and all treatments would be rated as having excellent color.

Site Comparison of Color Ratings

Turf color ratings at both the University and high school sites all had excellent turf color ratings. There were only small differences between treatments of 0.1 and 0.2 in color ratings. There was no clear evidence that saline substitution rate had any significant and consistent effect on turf color.

Cover Percentages

Average turfgrass cover percentages for the University site (Fig. 27) at the end of the two-year study period were all between 99 and 100 %. This would suggest that saline water application throughout the peak demand months for two growing periods could maintain excellent turfgrass quality.

Average turfgrass cover percentages for the high school site (Fig. 28) were 100 % for all treatments after the two-year study period. Cover values of 100 % indicate that substitution rate had no effect on turfgrass cover ratings.

Site Comparison of Cover Percentage

Cover percentages at both the University and high school sites were excellent at the end of the two-year study. Saline substitution rate had no clear effect on cover ratings at either site. The excellent cover ratings further substantiate that proper irrigation management was occurring.

Water Parameters

Sodium Adsorption Ratios (SAR)

At the University site sodium adsorption ratio (SAR) values ranged from 0.4 in the 2 out of 7 saline irrigation substitution treatment to 14.1 in the 1 out of 7 treatment. SAR data for the University site is shown for 1998 and 1999 respectively (Figs. 30 and 31). At the high school site SAR values ranged from 0.6 in the 1 out of 7 saline irrigation substitution treatment to 13.8 in the 2 out of 7 treatment. SAR data for the high school site is shown for 1998 and 1999 respectively (Figs. 32 and 33). However, average SAR values at both the University and high school sites were below 5.0 (Tables 13 and 14) at the end of the experimental period in May 1999.

Normalized SARs at the high school site stayed the same from May 1998 to May 1999 except for the 0-15 and 15-45 cm depths, which increased. Normalized SAR data at the University site could not be calculated because of missing data from the May 1997 soil sampling.

The number of samples required to estimate the mean depth weighted SAR for the 0-15 and 0-75 cm depth within 10% with 95% confidence was calculated (Table 15) for both the University and high school sites. The number of samples required was reached at the 0-15 cm depth at the University site for all treatments except the 1 out of 7 treatment and only the control treatment met the required number of samples at the 0-75 cm depth. At the high school only the 1 out of 7 treatment met the number of samples required at the 0-15 cm depth and the 1 out of 7 treatment and control at the 0-75 cm depth.

Canopy Temperature and Color vs. Soil Salinity and Water Saved

Canopy temperature and color ratings were plotted against soil salinity (ECe 0-45 cm) and average freshwater savings for the 1, 2, 3 and 4 out of 7 saline substitution treatments at the University site (Fig. 34). Large increases in water savings were associated with small increases in soil salinity in the 0-45 cm zone while excellent color ratings were maintained. The 4 out of 7 saline substitution treatment (worst case scenario) yielded the largest freshwater savings with small increases in soil salinity and at the same time with little or no impact in the turf quality. Average canopy temperatures rose by small amounts (0.9 °C) as the amount of freshwater savings increased (11.1 cm to 49.8 cm, i.e. as the saline substitution increased the amount of freshwater saved increased). As the saline substitution rate increased, average soil salinity increased only slightly (1.5 dSm^{-1}) and canopy temperatures on average increased 0.9 °C. These small subtle changes in canopy temperatures may be signaling a shift in plant water stress that could lead to a possible decline in turf quality. These trends would need to be verified over longer periods of time before any shift in substitution rate would be recommended.

3-Dimensional analyses of the same parameters at the high school site were also plotted. The color rating analysis yielded the same results as the University site but the canopy temperature vs. soil salinity and water savings was highly variable possibly due to the smaller data set (2 treatments at the high school site vs. 4 treatments at the University site).

Number of Days Saved

The average freshwater irrigation days saved at the University site per peak demand period (May 15 – Oct. 15) were 16.5, 32.0, 49.0 and 61.5 days for the 1, 2, 3 and 4 saline substitution treatments respectively (Fig. 35), showing that increased substitution rate increased irrigation days saved. The average freshwater that was saved per treatment increased proportionally with the number of days saved for each treatment.

The average freshwater irrigation days saved at the high school site per peak demand period (May 15 – Oct. 15) were 15.0 and 30.0 days for the 1 and 2 saline substitution treatments respectively (Fig. 36), showing that increased substitution rate also increased the number of freshwater days saved.

Cost Analysis

During the years of 1997 and 1998 an estimated cost of freshwater usage for irrigation of turfgrass at the UNLV experiment site was $18,164. This was estimated using the tiered rate schedule for a two-inch meter and the total gallons applied to the control plot extrapolated over the entire practice football field (Table 13).

The capital costs of the delivery system, which includes all materials, equipment, labor and unit costs, was estimated at $31,700 in 1997, which would project to $34,700 (3% increase/year) in 2000. This cost could be decreased if the existing delivery system could be used. Our research team provided most of the labor and therefore labor costs could be larger if installed by a professional crew.

Once installed the actual maintenance of the site and equipment was very small. An occasional monitoring of sprinkler heads and valve operation was all that was needed.

During the experimental period an average of 378,690 gallons of saline water was applied (for the 4 out of 7 treatment) each year during the peak demand months (May 15 – Oct. 15). This extrapolates out to 3,491,517 gallons for the entire turf area of the practice football field. The 4 out of 7 saline substitution treatment offers the greatest opportunity for water savings that is why it is being reported. Based on the tiered rate schedule that is currently paid by the University an annual cost of $5809 could be saved while using this system and the greater substitution rate. Assuming a rise in freshwater prices (Fig. 37) even larger benefits could be realized by the University. The feasibility to link existing systems around the practice football field to the well could be looked at to help increase freshwater and dollar savings.

Kriged Results

Kriged analysis was done for each plot at the University site and the high school site for soil salinity (0-15, 0-45 and 0-75 cm), EM 38, soil moisture (theta probe), gravimetric water content, canopy temperature, color ratings and cover percentages. Only certain parameters that have distinguishable patterns will be discussed for the 1 and 4 out of 7 saline substitution treatments at the University site at the end of the experimental period, May 1999. To allow for easier visual comparison the range (based on evaluating the data from all plots) within the contour map was held the same for each parameter. A comparison of kriged contour maps of soil salinity for the 1 and 4 out of saline substitution treatments at the 0-15 and 0-75 cm depth showed that as the depth decreased the soil salinity dropped to between 3.0 and 5.0 dSm^{-1} showing that high and low substitution treatments responded in similar fashion spatially (Fig. 38). Horizontally adjusted EM 38 values and gravimetric water content showed a trend of increasing soil conductivity with increasing water content to the northwest in the 4 out of 7 treatment (Fig. 39). Water content was shown to have a large impact on EM 38 values at the University site (depth weighted gravimetric water = 0.008 + 0.006 * horizontally adjusted EM 38 value, r = 0.84***). A similar pattern was observed in the 1 out of 7 treatment as conductivity increased over the plot to the northeast and gravimetric water content could be seen following a similar pattern (Fig. 40). Higher canopy temperatures in the 1 out of 7 treatment were seen in the northwest portion of the plot indicating that plant stress was higher in areas of lower water content. For both the 1 and 4 out of 7 treatments color ratings and cover percentages were excellent at the end of the experimental period indicating that soil salinity and gravimetric water content had little effect on the overall quality of the turfgrass.

CHAPTER VII

SUMMARY, CONCLUSIONS, RECOMMENDATIONS

With demand for freshwater resources increasing in the southwestern U.S., utilizing waters of poor quality for the irrigation of urban landscapes needs greater evaluation. This is especially true for large areas of turfgrass. A study was conducted in the Las Vegas Valley at the University of Nevada Las Vegas practice football field and at the Valley High School soccer field to determine the feasibility of using a shallow saline aquifer to irrigate large areas of turfgrass, primarily bermudagrass overseeded with ryegrass. In the Las Vegas Valley a shallow saline groundwater system (estimated at 100,00 acre feet) exists just beneath the surface. We investigated the potential use of this water as an alternative irrigation source. The shallow groundwater was pumped into a parallel delivery system and cycled on during the peak demand months of May through October, with freshwater being used as the sole source during the non-peak demand months of November through April.

Rhoades (1977) was one of the first to suggest irrigation alternatives to using waters of poor quality. Previous studies have shown that saline water can be used on agricultural crops (Ayars 1986a; Dinar et al. 1986; Grattan et al. 1987; Levy et al. 1999) and non-agricultural crops like turfgrass (Ackerson and Younger1975; Dean et al. 1996; Peacock and Dudeck 1985a; Dudeck et al. 1983; Devitt 1989; Devitt et al. 1990; Leskys 1999; Hayes et al. 1990; Francois 1988). In Israel, the long-term use of relatively high saline water was shown to be successful in the growing of commercial crops such as, wheat, sorghum, sweet corn, cotton, tomato, beet, celery, melon, and lettuce (Pasternak et al. 1984). Dinar and Letey (1986) performed a study to determine optimal ratios of saline water to nonsaline water and found that the technical and economic feasibility of mixing waters of different quality increases as the EC of the saline water decreases, crop tolerance to salinity increases, desired relative yield decreases and the relative price of the saline water to nonsaline water decreases. Water quality at both the University (3.3 dSm^{-1}) and high school (1.8 dSm^{-1}) sites would suggest that this water could be used at various substitution rates for the irrigation of turfgrass. Dean et al. (1996) showed that water with a salinity of 6.0 dSm^{-1} could be used to irrigate turfgrass without a decrease in color values or cover percentages. Leskys et al. (1999) showed that when irrigating with saline water (2.5 dSm^{-1}), maintaining the highest possible uniformity coefficient (CUC) enables the leaching fraction (LF) to be minimized and water savings to occur while obtaining favorable soil salinity and plant response. Francois (1988) showed that two different bermudagrass cultivars 'Tifton II' and Tifton 86 were unaffected by ECe's below 8.4 and 10.4 dSm^{-1} respectively, under well watered conditions.

Estimating evapotranspiration on at least a weekly basis is critical in scheduling irrigations to achieve low leaching fractions (Devitt et al. 1983). Lower leaching fractions ensure that excess irrigation water does not percolate beyond the root zone taking high amounts of salt into the groundwater. As ETo increased rapidly during the beginning of the saline irrigation season (May - June), irrigations based on the previous weeks estimated ET were slightly out of sync with the current weeks ETo. It was during this phase of the bell shaped ETo curve that greater matric and osmotic oscillations occurred. Based on these observations we concluded that it is critical during spring and early summer to use shorter periods of time to estimate ET to fine-tune the irrigation amounts.

Salinity sensor results showed that the cycling of saline water on during the peak demand months of May to October caused soil salinity values at the University site to exceed the threshold value of 13.8 dSm^{-1} in the soil water (Figs. 3, 5 and 6). However, the subsequent off period during the months of October 15 to May 15 was shown to bring soil salinity back to baseline values (~ 3.0 - 8.0 dSm^{-1}) at both sites. This reclamation period was similar to that found in research done by Sharma and Rao (1998), which suggested that using an irrigation strategy that combined the use of good quality and poor quality water for different portions of the irrigation season could be acceptable as long as soil salinity was closely monitored to insure that plant stress was minimized. The salinity level of the irrigation water that can be tolerated depends not only on the salt tolerance of the crop to be grown, but also on the initial content and distribution of salts in the soil profile, on the amount and frequency of irrigation, on the extent to which the soil water is depleted between irrigations, and on the water content and matric properties of the soil (Hamdy 1996).

It has been shown that growth, color and cover of turfgrass declines in response to a combination of matric and osmotic induced stress (Devitt et al. 1993). Results from this study showed that increases in soil salinity during the peak summer months had little effect on color and cover ratings. Previous work by Dean et al. (1996) showed that when maintaining an I/ETo value of 0.80 for tall fescue and 0.65 for bermudagrass no decline in cover or color was observed. An I/ETo value of 0.96 was averaged over the two-year experimental period for the 4 out of 7 treatment at the University site, associated with high color and cover values. Dean et al. (1996) also showed that canopy temperature is a better indicator of plant stress and is an easy parameter to assess and is more closely correlated with growth parameters. Our results showed little correlation between 0-15 cm ECe and canopy temperature at the University ($r^2 = 0.05$) or high school site ($r^2 = 0.32$) for all treatments. These results were for the end of the experimental period representing a freshwater recovery period from November to May. However, our results did show a correlation between tissue moisture and canopy temperature ($r^2=0.08$, $p=0.01$) at the University site but no correlation between leaf xylem water potential and canopy temperature when the two largest substitution treatments (3 and 4 out of 7) were combined.

Irrigation techniques, such as blending, and seasonal or cyclic irrigation have been demonstrated to maintain soil salinity levels below species dependent tolerant limits and to minimize the negative effects on plant growth (Bradford and Letey 1992). The use of such techniques combined with root zone monitoring can minimize matric and osmotic potential oscillations. We found that as the matric potentials became lower than -0.12 MPa, soil salinity oscillated upwards to as high as 23.0 dSm^{-1} at the 40 cm depth in the 1 out of 7 saline treatment at the University but no distinguishable pattern was seen between treatments at either site. These oscillations in soil salinity and matric potential had no observable effect on measured plant parameters. This could be due to the fact that the stress was not maintained for long periods of time due to irrigations being based on an ET feedback system with a 0.15 imposed LF and because of the positive effect of cycling on freshwater between saline irrigations. Since soil salinity was typically higher near the surface and lower at depths below 75 cm where applied salts had not arrived, we can not rule out the possibility of a higher fractional water uptake in these zones of more favorable osmotic potential. However, if wider oscillations in the matric potential and soil salinity occurred in combination with complete profile salinization a negative plant response would most likely have been observed.

The long-term use of the shallow saline aquifer system depends on many factors, such as, depth to water table, aquifer yield, water quality, build-up of soil solutes, SAR and infiltration, availability of storage or blending facilities, the presence of environmental contaminants and the associated costs of maintaining the well, pump and delivery system. Our study showed that a cyclic irrigation strategy using the shallow groundwater could be used while causing little increase in soil salinity and SAR during a two-year on/off period. Average 0-75 cm depth weighted soil salinities for all treatments at the University site decreased 0.1 dSm^{-1} from 4.4 dSm^{-1} in 1997 to 4.3 dSm^{-1} in1999 and at the high school site rose 1.1 dSm^{-1} from 5.0 dSm^{-1} in 1997 to 6.1 dSm^{-1} in 1999. This small increase at the high school site was most likely associated with a redistribution of salts from the upper soil profile and the attainment of a steady state leaching fraction greater than 0.20, compared to what we believe was an extended imposed deficit irrigation regime during pre-experimental times.

Over 3900 soil samples were taken from the treatment plots during the course of this two-year field study. Major emphasis was placed on assessing ECe and SAR at the different depths. A tight correlation did not exist between the salinity sensors and saturation extract salinities even after field moisture corrections. This we believe was due to spatial variability and a phase lag associated with the sensors. The sensors were useful as a feedback mechanism to assess cyclic trends, depth distributions and if threshold values were being exceeded. The soil samples we believe gave a more credible assessment of the spatial distribution of salts at a specific window in time.

The sample numbers required to estimate depth weighted soil salinity (ECe) and SAR at both sites within 10% of the mean at the 95% confidence level were calculated and reported in Tables 10 and 15 respectively. It was shown that the number of samples needed to determine soil salinity was lower for all treatments at both sites than was taken. This was in line with Leskys et al. (1999) who found that soil salinity samples were lower for plots with high leaching fractions (0.20) and high uniformity coefficients (0.80). However, the number of samples needed to estimate SAR varied between treatments and sites with large sample numbers needed for the 0-75 cm depth at the University. In some cases a more intensive grid would have been justified. However, the amount of time needed for such large-scale sampling (>300 samples) may not be cost effective.

The increase in substitution rates obviously increased the amount of salts applied to the soil through the irrigation water. Even though we saw oscillations in soil water salinity throughout the experiment, the soil salinity measured from final soil cores showed that increased substitution rate had little effect on the depth weighted soil salinity. However, we believe this was largely due to a redistribution effect and not having attained a steady state salt balance. Geostatistical analysis of the soil salinity data (ECe) revealed that, the spatial distribution of salts was fairly uniform at all depths regardless of treatment and site. This was anticipated since the irrigation uniformities were above 0.8 and the projected leaching fractions were greater than 0.20 at both the University and high school sites, which would be in agreement with the results of Leskys et al. (1999). This spatial distribution of salts at the near soil surface had little effect on plant parameters such as, color ratings and cover percentages. Kriged results of color and cover showed no distinguishable pattern when compared to near soil surface salinity (0-15 cm) isopleths.

Increasing the saline substitution rate decreases the irrigation interval between saline applications. It has been shown that frequent irrigations with saline water leads to a much greater increase in salt accumulation at the soil surface (Bernstein and Francois 1973), which can lead to a decline in plant growth. We found that average normalized soil salinity (ECe) for the 0-15 cm depth at the University site increased with increasing saline substitution rate (1.1, 1.2, 1.4 and 1.5 for the 1, 2, 3 and 4 out of 7 treatments respectively) from 1997 to 1999. At the high school site we found that the 1 out of 7 treatment had the higher normalized increase in soil salinity (1.6) at the 0-15 cm depth. The 15-45 cm increment at the University site showed an increase in the 4 out of 7 and control to 1.1 and 1.2 respectively and in the 45-75 cm depth all treatments remained the same or declined except for control, which increased to 1.1.

Color ratings, cover percentages and canopy temperature (canopy temperature minus ambient temperature) at both the University and high school sites were shown to oscillate with time of year which coincided with environmental demand and the amount of water applied. Color ratings for all treatments at the end of the experiment (May 1999) where higher than 1997 values at both sites. This color increase was likely due to improved nitrogen and soil water status over pre-experimental conditions. Cover percentages were higher during the peak demand months but oscillated during the off periods of saline irrigation and showed little response to increased saline substitution rate at both sites.

The decline during the off periods was due to the bermudagrass moving into dormancy and a lag period associated with germination and establishment of the overseeded ryegrass. An increasing trend in canopy temperature was seen at the end of the experiment at both sites. Plant response (water and salt uptake) to increasing soil salinity (Fig. 34) especially at the surface was no doubt contributing to this subtle increase in canopy temperature and was a factor that should be monitored closely when using saline water for extended periods.

The cost benefits of using waters of poor quality such as the shallow saline aquifer could be significant for entities that have large areas of turfgrass to irrigate. Freshwater savings for the 4 out of 7 saline substitution treatment at the University site was estimated to be $5809 during the peak demand period (May15 to Oct. 15) when extrapolated out over the entire playing surface (22,555 m^2 with a 2" meter and corresponding costs). The amount of money saved would obviously increase as water price increases. If one assumes an average utility rate increase trended on the ten-year historical average (Fig. 37), water prices might reach $4.50 per 1000 gallons. Dollar savings associated with this higher water rate could increase to approximately $11,712 for the entire field.

In addition to the financial benefits of using the shallow saline aquifer system, freshwater irrigation days were also saved. During peak demand months 62 freshwater irrigation days were saved with the 4 out of 7 saline substitution treatment at the University site (Fig. 35) and 30 days were saved at the high school site (Fig. 36) for the 2 out of 7 saline substitution treatment. Freshwater days saved puts less demand on the freshwater delivery system as well as providing greater flexibility to irrigators to complete irrigations on large areas of turfgrass.

There are few experiments that have investigated the use of saline water for long-term irrigation. Most experiments have been done on a small scale and more research needs to be done to assess the large-scale effects. Before implementing a saline irrigation strategy over a large area, the long-term environmental and economic impacts need to be investigated. The availability and quality of the water sources to be used as well as the irrigation management to be imposed will dictate the long-term use and sustainability of the system (Grattan 1994). Most studies including this one have demonstrated the key to long-term use, is maintaining a favorable salt-balance within the soil. This balance must ensure that the physical and chemical properties of the soil do not alter internal drainage nor negatively influence the health and overall productivity of the plants being grown.

There are limitations to consider when using the shallow saline aquifer system. One limitation is location. Some locations may not be suited for use of this water because of too high of a salinity level. Aquifer water can vary in salinity from 1.8 dSm^{-1} at the high school site to over 8.0 dSm^{-1} near the Clark County Sanitation District. Aquifer yield can be another limitation as was evident at the high school site which limited our treatment plots to 2, as the 8.0 gpm yield from the shallow aquifer was not great enough to meet irrigation needs. Although the shallow groundwater system is estimated at 100,000 acre-feet only a portion of the golf courses, parks and schools are currently located in the general area of the shallow system. However, as the price of freshwater continues to increase, the cost of pumping this water to locations outside of the shallow groundwater area may become economically feasible. Finally, it must also be realized that drainage entering the shallow system after reuse will carry a higher salt load. As the salinity of the shallow system increases, substitution rates will have to be adjusted downward.

However, until the system becomes too saline for any economical substitution rate to occur, using this water to reduce the size of the shallow system (classified as a nuisance water) in a way that frees up good quality water for higher priority uses would be beneficial. In conclusion, results were favorable for the use of a cyclic irrigation strategy, utilizing shallow saline aquifer water and freshwater during peak demand months. However, use of the shallow aquifer system will require constant soil and plant monitoring to adjust substitution rates and leaching fractions to minimize the time period in which species specific threshold values are exceeded.

APPENDIX A

TABLES

Table 1. Shallow saline aquifer water characteristics for both the University and high school sites compared to municipal water

		UNLV	High School	Municipal
EC	(dSm^{-1})	3.28	1.83	0.86
Na^+	(meql^{-1})	7.21	5.36	3.31
K^+	(meql^{-1})	0.30	0.30	0.02
Ca^{2+}	(meql^{-1})	15.73	6.18	3.45
Mg^{2+}	(meql^{-1})	21.55	10.43	2.99
Cl^-	(meql^{-1})	4.68	3.50	2.66
HCO_3^-	(meql^{-1})	3.96	4.38	2.45
CO_3^{2-}	(meql^{-1})	0.09	0.16	0.00
SO_4^{2-}	(meql^{-1})	32.67	14.01	4.63
pH		8.0	8.10	8.0
SAR_{Adj}		4.7	4.8	3.8

Table 2. Average soil salinity (ECe, dSm^{-1}) at the University site before salinization (1997) for all treatments.

	Depth of Sampling														
	0-15 cm			15-45 cm			45-75 cm			0-45 cm			0-75 cm		
Saline Irrigation Substitution Rate	Avg.	Std. dev.	n	Avg.	Std. dev.	n	Avg.	Std. dev.	n	Avg.	Std. dev.	n	Avg.	Std. dev.	n
	dSm^{-1}														
1 out of 7	5.0	0.8	32	4.6	1.1	32	4.2	0.6	6	4.7	0.9	32	4.8	0.8	6
2 out of 7	4.7	0.9	32	4.7	0.7	32	3.6	0.5	6	4.7	0.7	32	4.3	0.8	6
3 out of 7	3.9	1.3	32	4.5	1.3	32	5.3	1.4	6	4.3	1.2	32	5.2	1.1	6
4 out of 7	4.0	1.3	32	4.3	1.2	32	4.3	1.2	6	4.2	1.2	32	4.5	1.6	6
Control	3.7	0.5	32	3.5	0.6	32	3.2	0.2	6	3.6	0.5	32	3.3	0.2	6

Table 3. Average soil salinity (ECe, dSm^{-1}) at the high school site before salinization (1997) for all treatments.

	Depth of Sampling														
	0-15 cm			15-45 cm			45-75 cm			0-45 cm			0-75 cm		
Saline Irrigation Substitution Rate	Avg.	Std. dev.	n	Avg.	Std. dev.	n	Avg.	Std. dev.	n	Avg.	Std. dev.	n	Avg.	Std. dev.	n
							dSm^{-1}								
1 out of 7	3.6	0.4	16	4.2	0.7	16	5.3	0.6	3	4.0	0.6	16	4.7	0.69	3
2 out of 7	4.6	1.0	16	4.2	0.5	15	3.9	0.4	3	4.2	1.0	16	4.3	0.74	3
Control	6.0	1.6	6	6.0	0.8	6	5.3	0.5	6	6.1	1.0	6	5.8	0.73	6

Table 4. Average salinity sensor values (dSm^{-1}) for each ON and OFF period at the University site throughout the experimental period Jan. 1, 1997 to May 15, 1999.

SALINE IRRIGATION STATUS DURING THE EXPERIMENT

Saline Irrigation Substitution Rate		OFF 1			ON 1			OFF 2			ON 2			OFF 3		
		Avg.	Std. dev.	n	Avg.	Std. dev.	n	Avg.	Std. dev.	n	Avg.	Std. dev.	n	Avg.	Std. dev.	n
		dSm^{-1}			dSm^{-1}			dSm^{-1}			dSm^{-1}			dSm^{-1}		
1 out of 7	10 cm	7.5	1.2	30	9.1	3.1	42	7.3	1.0	30	8.2	1.8	38	8.0	1.0	18
	25 cm	8.5	2.1	30	11.7	4.0	42	9.3	1.3	30	12.7	3.1	38	8.3	1.6	18
	40 cm	10.9	2.5	30	14.7	4.6	42	9.8	1.7	30	15.8	3.1	38	8.6	1.9	18
2 out of 7	10 cm	4.8	1.2	30	6.9	1.9	42	6.3	1.2	30	7.7	1.1	38	7.1	1.1	17
	25 cm	4.3	1.0	30	7.2	1.7	42	5.6	1.2	30	6.9	0.9	38	6.3	0.5	18
	40 cm	4.6	0.8	29	8.8	1.5	42	6.1	1.2	30	7.7	0.8	38	6.6	0.6	18
3 out of 7	10 cm	4.6	1.5	30	7.9	1.8	42	6.2	0.9	30	8.8	1.2	38	7.6	1.2	18
	25 cm	7.2	1.9	30	8.5	1.6	42	7.0	0.8	30	8.4	2.0	38	8.2	0.8	17
	40 cm	10.1	3.2	30	14.9	4.8	42	8.6	1.2	30	12.4	2.6	38	9.0	1.0	18
4 out of 7	10 cm	4.2	1.2	30	6.9	1.5	42	8.1	1.3	30	11.0	3.2	38	6.8	1.3	18
	25 cm	4.5	0.8	30	7.0	1.2	42	6.8	1.4	30	10.2	4.2	37	7.4	2.0	18
	40 cm	3.5	1.0	30	6.0	0.5	42	5.1	2.2	29	9.1	2.3	37	6.9	1.2	18

Table 5. Average salinity sensor values (dSm^{-1}) for each ON and OFF period at the high school site throughout the experimental period Jan. 1, 1997 to May 15, 1999

SALINE IRRIGATION STATUS DURING THE EXPERIMENT

Saline Irrigation Substitution Rate		OFF 1			ON 1			OFF 2			ON 2			OFF 3		
		Avg.	Std. dev.	n	Avg.	Std. dev.	n	Avg.	Std. dev.	n	Avg.	Std. dev.	n	Avg.	Std. dev.	n
		dSm^{-1}			dSm^{-1}			dSm^{-1}			dSm^{-1}			dSm^{-1}		
1 out of 7	10 cm	2.8	1.0	27	3.0	1.0	40	3.2	1.2	30	4.2	1.0	42	3.8	1.0	22
	25 cm	3.8	1.3	31	4.3	1.1	40	3.6	1.0	26	5.4	0.9	39	4.6	0.8	22
	40 cm	4.3	1.0	29	5.6	0.8	40	4.5	1.3	29	6.8	1.7	42	5.8	1.6	22
2 out of 7	10 cm	6.8	1.9	31	5.4	1.6	38	4.0	1.5	30	5.4	1.3	42	5.3	1.8	22
	25 cm	3.8	0.7	32	4.6	0.9	38	3.9	0.8	26	4.9	0.7	40	4.5	1.2	22
	40 cm	2.7	0.8	31	3.1	0.7	34	3.3	0.8	29	4.2	0.7	42	4.5	1.3	22

Table 6. Soil salinity (ECe, dSm^{-1}) at the University site for all depths and treatments from April 1997, May 1998 and May 1999

Saline Irrigation Substitution Rate		Depth of Sampling (cm) 0-15 Avg.	0-15 Std. Dev.	0-15 n	15-45 Avg.	15-45 Std. Dev.	15-45 n	45-75 Avg.	45-75 Std. Dev.	45-75 n	0-45 Avg.	0-45 Std. Dev.	0-45 n	0-75 Avg.	0-75 Std. Dev.	0-75 n
		dSm^{-1}			dSm^{-1}			dSm^{-1}			dSm^{-1}			dSm^{-1}		
1 out of 7	1997	5.0	0.8	32	4.6	1.1	32	4.2	0.6	6	4.7	0.9	32	4.8	0.8	6
	1998	4.7	0.9	50	4.9	1.4	50	4.5	1.0	49	3.9	0.8	50	4.7	1.0	50
	1999	5.7	1.3	49	4.6	1.6	50	3.9	1.2	50	4.9	1.4	49	4.5	1.3	49
2 out of 7	1997	4.7	0.9	32	4.7	0.7	32	3.6	0.5	6	4.7	0.7	32	4.3	0.8	6
	1998	4.6	0.9	47	5.1	0.9	50	5.1	1.1	49	4.9	0.8	47	5.1	0.9	45
	1999	5.6	0.9	50	4.6	1.0	50	3.5	0.8	50	4.9	0.9	50	4.3	0.8	50
3 out of 7	1997	3.9	1.3	32	4.5	1.3	32	5.3	1.4	6	4.3	1.2	32	5.2	1.1	6
	1998	4.7	1.0	49	4.9	1.3	49	4.8	1.6	49	4.8	1.1	48	4.8	1.3	46
	1999	5.6	0.9	50	4.6	1.1	50	3.8	0.8	50	5.0	1.0	50	4.5	0.9	50
4 out of 7	1997	4.0	1.3	32	4.3	1.2	32	4.3	1.2	6	4.2	1.2	32	4.5	1.6	6
	1998	3.6	1.0	50	4.6	1.0	50	4.2	0.7	49	4.2	1.0	50	4.2	0.8	50
	1999	5.8	0.7	50	4.8	0.7	50	3.7	0.5	50	5.1	0.6	50	4.6	0.5	50
Control	1997	3.7	0.5	32	3.5	0.6	32	3.2	0.2	6	3.6	0.5	32	3.3	0.2	6
	1998	3.4	0.6	50	4.0	0.8	50	4.3	1.2	50	3.8	0.6	50	4.0	0.8	50
	1999	4.0	0.8	49	4.1	0.6	50	3.4	0.4	49	4.1	0.6	49	3.8	0.5	49

Table 7. Soil salinity (ECe, dSm^{-1}) at the high school site for all depths and treatments from April 1997, May 1998 and May 1999

Depth of Sampling (cm)

Saline Irrigation Substitution Rates		0-15			15-45			45-75			0-45			0-75		
		Avg.	Std. Dev.	n	Avg.	Std. Dev.	n	Avg.	Std. Dev.	n	Avg.	Std. Dev.	n	Avg.	Std. Dev.	n
		dSm^{-1}			dSm^{-1}			dSm^{-1}			dSm^{-1}			dSm^{-1}		
1 out of 7	1997	3.6	0.4	16	4.2	0.7	16	5.3	0.6	3	4.0	0.6	16	4.7	0.7	3
	1998	3.6	0.7	50	4.2	0.7	50	4.7	0.6	45	4.0	0.7	50	4.1	0.9	50
	1999	5.8	1.6	50	5.8	1.3	50	5.3	1.2	50	5.8	1.3	50	5.6	1.1	50
2 out of 7	1997	4.6	1.0	16	4.2	0.5	15	3.9	0.4	3	4.2	1.0	16	4.3	0.7	3
	1998	4.8	1.2	49	5.2	1.3	50	4.8	0.9	50	5.0	1.2	50	4.9	1.0	50
	1999	6.1	1.7	50	6.1	1.3	50	5.2	1.3	50	6.1	1.3	50	5.8	1.2	50
Control	1997	6.0	1.6	6	6.0	0.8	6	5.3	0.5	6	6.1	1.0	6	5.8	0.7	6.0
	1998	5.9	1.5	50	6.8	1.0	50	6.1	0.7	50	6.5	1.1	50	6.3	0.7	50
	1999	7.5	2.1	50	7.3	1.3	50	7.3	1.3	50	7.3	1.4	50	6.9	1.0	50

Table 8. Normalized soil salinity (ECe, dSm^{-1}) at the University site for all depths and treatments from April 1997, May 1998 and May 1999

Saline Irrigation Substitution Rate		Depth of Sampling (cm) 0-15			15-45			45-75			0-45			0-75		
		Avg.	Norm	n	Avg.	Norm	n	Avg.	Norm	n	Avg.	Norm	n	Avg.	Norm	n
		dSm^{-1}			dSm^{-1}			dSm^{-1}			dSm^{-1}			dSm^{-1}		
	1997	5.0	1.0	32	4.6	1.0	32	4.2	1.0	6	4.7	1.0	32	4.8	1.0	6
1 out of 7	1998	4.7	0.9	50	4.9	1.1	50	4.5	1.1	49	3.9	0.8	50	4.7	1.0	50
	1999	5.7	1.1	49	4.6	1.0	50	3.9	0.9	50	4.9	1.0	49	4.5	0.9	49
	1997	4.7	1.0	32	4.7	1.0	32	3.6	1.0	6	4.7	1.0	32	4.3	1.0	6
2 out of 7	1998	4.6	1.0	47	5.1	1.1	50	5.1	1.4	49	4.9	1.0	47	5.1	1.2	45
	1999	5.6	1.2	50	4.6	1.0	50	3.5	1.0	50	4.9	1.0	50	4.3	1.0	50
	1997	3.9	1.0	32	4.5	1.0	32	5.3	1.0	6	4.3	1.0	32	5.2	1.0	6
3 out of 7	1998	4.7	1.2	49	4.9	1.1	49	4.8	0.9	49	4.8	1.1	48	4.8	0.9	46
	1999	5.6	1.4	50	4.6	1.0	50	3.8	0.7	50	5.0	1.2	50	4.5	0.9	50
	1997	4.0	1.0	32	4.3	1.0	32	4.3	1.0	6	4.2	1.0	32	4.5	1.0	6
4 out of 7	1998	3.6	0.9	50	4.6	1.1	50	4.2	1.0	49	4.2	1.0	50	4.2	0.9	50
	1999	5.8	1.5	50	4.8	1.1	50	3.7	0.9	50	5.1	1.2	50	4.6	1.0	50
	1997	3.7	1.0	32	3.5	1.0	32	3.2	1.0	6	3.6	1.0	32	3.3	1.0	6
Control	1998	3.4	0.9	50	4.0	1.1	50	4.3	1.3	50	3.8	1.1	50	4.0	1.2	50
	1999	4.0	1.1	49	4.1	1.2	50	3.4	1.1	49	4.1	1.1	49	3.8	1.2	49

Table 9. Normalized soil salinity (ECe, dSm^{-1}) at the high school site for all depths and treatments from April 1997, May 1998 and May 1999

Depth of Sampling (cm)

Saline Irrigation Substitution Rates		0-15			15-45			45-75			0-45			0-75		
		Avg.	Norm.	n	Avg.	Norm.	n	Avg.	Norm.	n	Avg.	Norm.	n	Avg.	Norm.	n
		dSm^{-1}			dSm^{-1}			dSm^{-1}			dSm^{-1}			dSm^{-1}		
1 out of 7	1997	3.6	1.0	16	4.2	1.0	16	5.3	1.0	3	4.0	1.0	16	4.7	1.0	3
	1998	3.6	1.0	50	4.2	1.0	50	4.7	0.9	45	4.0	1.0	50	4.1	0.9	50
	1999	5.8	1.6	50	5.8	1.4	50	5.3	1.0	50	5.8	1.5	50	5.6	1.2	50
2 out of 7	1997	4.6	1.0	16	4.2	1.0	15	3.9	1.0	3	4.2	1.0	16	4.3	1.0	3
	1998	4.8	1.0	49	5.2	1.2	50	4.8	1.2	50	5.0	1.2	50	4.9	1.1	50
	1999	6.1	1.3	50	6.1	1.5	50	5.2	1.3	50	6.1	1.5	50	5.8	1.3	50
Control	1997	6.0	1.0	6	6.0	1.0	6	5.3	1.0	6	6.1	1.0	6	5.8	1.0	6.0
	1998	5.9	1.0	50	6.8	1.1	50	6.1	1.2	50	6.5	1.1	50	6.3	1.1	50
	1999	7.5	1.3	50	7.3	1.2	50	7.3	1.4	50	7.3	1.2	50	6.9	1.2	50

Table 10. Number of samples required to estimate the mean soil salinity (ECe) within 10% at the 95% confidence level at both the University and high school sites.

University site			High School site		
Treatment	Sample Depth 0 -15 cm	Sample Depth 0 -75 cm	Treatment	Sample Depth 0 -15 cm	Sample Depth 0 -75 cm
1 out of 7	21	32	1 out of 7	30	17
2 out of 7	10	14	2 out of 7	30	16
3 out of 7	10	14	Control	31	9
4 out of 7	5	5			
Control	14	7			

Table 11. Normalized salinity sensor values (dSm^{-1}) at the University site for the experimental period May 15 ,1997 to May 15, 1999

Saline Irrigation Substitution Rate	OFF 1	ON 1	OFF 2	ON 2	OFF 3	OFF 1	ON 1	OFF 2	ON 2	OFF 3	OFF 1	ON 1	OFF 2	ON 2	OFF 3
	10 cm					25 cm					40 cm				
1 out of 7	1.0	1.2	1.0	1.1	1.1	1.0	1.4	1.1	1.5	1.0	1.0	1.3	0.9	1.5	0.8
2 out of 7	1.0	1.4	1.3	1.6	1.5	1.0	1.7	1.3	1.6	1.5	1.0	1.9	1.3	1.7	1.4
3 out of 7	1.0	1.7	1.3	1.9	1.6	1.0	1.2	1.0	1.2	1.1	1.0	1.5	0.9	1.2	0.8
4 out of 7	1.0	1.6	1.9	2.6	1.6	1.0	1.5	1.5	2.2	1.6	1.0	1.7	1.5	2.6	2.0

	1 out of 7	2 out of 7	3 out of 7	4 out of 7		1 out of 7		3 out of 7	4 out of 7		1 out of 7	2 out of 7	3 out of 7	4 out of 7
ON 1	1.2	1.4	1.7	1.6	ON 1	1.4	2 out of 7	1.2	1.5	ON 1	1.3	1.9	1.5	1.7
OFF1	1	1.3	1.3	1.0	OFF1	1.1	1.7	1	1.5	OFF1	0.9	1.3	0.9	1.5
ON2	1.1	1.6	1.9	2.6	ON2	1.5	1.3	1.2	2.2	ON2	1.5	1.7	1.2	2.6
OFF2	1.1	1.5	1.6	1.6	OFF2	1	1.6	1.1	1.6	OFF2	0.8	1.4	0.8	2

Table 12. Normalized salinity sensor values (dSm^{-1}) at the high school site for the experimental period May 15 ,1997 to May 15, 1999

Saline Irrigation Substitution Rate	OFF 1	ON 1	OFF 2	ON 2	OFF 3	OFF 1	ON 1	OFF 2	ON 2	OFF 3	OFF 1	ON 1	OFF 2	ON 2	OFF 3
	10 cm					25 cm					40 cm				
1 out of 7	1.0	1.1	1.1	1.5	1.4	1.0	1.1	0.9	1.4	1.2	1.0	1.3	1.0	1.6	1.3
2 out of 7	1.0	0.8	0.6	0.8	0.8	1.0	1.2	1.0	1.3	1.2	1.0	1.1	1.2	1.6	1.7

Table 13. Average SAR values for the University site for all depths and treatments for May 1999.

	Depth of Sampling																				
	0-15 cm			15-45 cm			45-75 cm			75-105 cm			105-135 cm			135-165 cm			165-195 cm		
Saline Irrigation Susbstitution Rate	Avg.	Std. Dev.	n	Avg.	Std. Dev.	n	Avg.	Std. Dev.	n	Avg.	Std. Dev.	n	Avg.	Std. Dev.	n	Avg.	Std. Dev.	n	Avg.	Std. Dev.	n
1 out of 7	3.7	1.9	43	3.4	3.1	49	3.1	2.7	48	3.5	2.3	45	3.5	1.1	5	3.9	1.2	3	3.6	1.2	3
2 out of 7	3.1	0.7	50	2.7	1.7	50	1.8	1.7	50	2.2	1.7	50	2.5	1.3	6	3.1	1.7	5	2.5	1.1	2
3 out of 7	3.1	1.0	50	2.5	1.8	50	2.3	1.8	49	2.6	1.8	50	2.7	1.0	6	3.1	1.4	6	3.3	1.7	3
4 out of 7	3.0	0.5	50	2.4	1.0	50	2.1	1.2	49	2.9	1.4	48	2.8	0.5	6	2.3	0.9	6	2.7	1.0	6
Control	2.7	0.8	50	2.4	0.9	50	1.5	0.6	49	1.8	0.8	41	2.3	0.8	3	2.0	0.9	2	1.2	N/A	1

Average SAR values for the high school site for all depths and treatments for May 1999.

Depth of Sampling

Saline Irrigation Susbstitution Rate	0-15 cm Avg.	0-15 cm Std. Dev.	0-15 cm n	15-45 cm Avg.	15-45 cm Std. Dev.	15-45 cm n	45-75 cm Avg.	45-75 cm Std. Dev.	45-75 cm n	75-105 cm Avg.	75-105 cm Std. Dev.	75-105 cm n	105-135 cm Avg.	105-135 cm Std. Dev.	105-135 cm n	135-165 cm Avg.	135-165 cm Std. Dev.	135-165 cm n	165-195 cm Avg.	165-195 cm Std. Dev.	165-195 cm n
1 out of 7	4..7	1.1	49	4.5	1.3	50	3.7	1.2	50	3.7	1.5	50	4.1	1.4	6	4.0	1.4	6	2.8	1.0	6
2 out of 7	4.6	3.2	49	4.8	3.2	50	3.6	2.4	50	2.7	0.9	50	2.9	0.8	4	2.5	1.0	6	2.2	0.8	6
Control	6.3	3.0	50	7.0	2.3	50	4.2	1.5	50	3.0	1.5	49	3.0	1.5	6	4.4	1.6	6	4.8	1.8	6

Table 15. Number of samples required to estimate the mean depth weighted SAR within 10% at the 95% confidence level at both the University and high school sites.

University site			High School site		
Treatment	Sample Depth 0 -15 cm	Sample Depth 0 -75 cm	Treatment	Sample Depth 0 -15 cm	Sample Depth 0 -75 cm
1 out of 7	108	253	1 out of 7	22	28
2 out of 7	21	137	2 out of 7	196	159
3 out of 7	42	145	Control	92	40
4 out of 7	11	57			
Control	35	37			

APPENDIX B

FIGURES

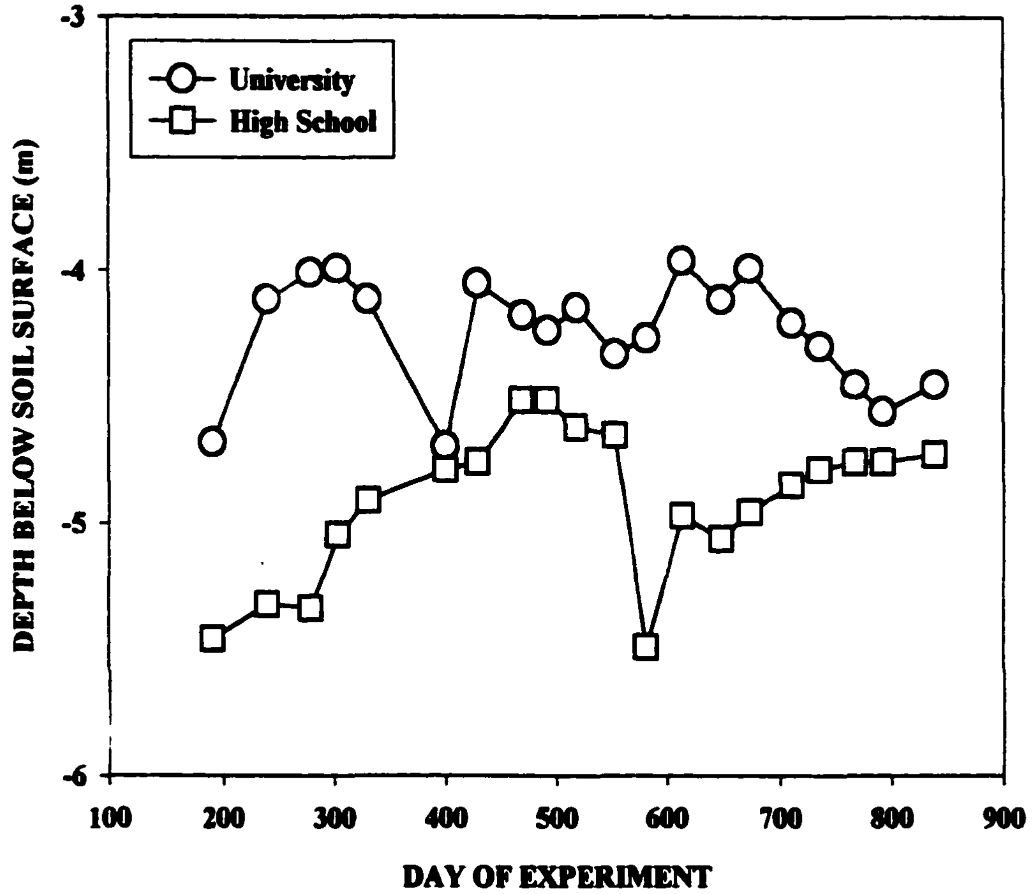

Fig. 1. Well water depth for both the University and high school sites for the experimental period May 15, 1997 - May 15, 1999

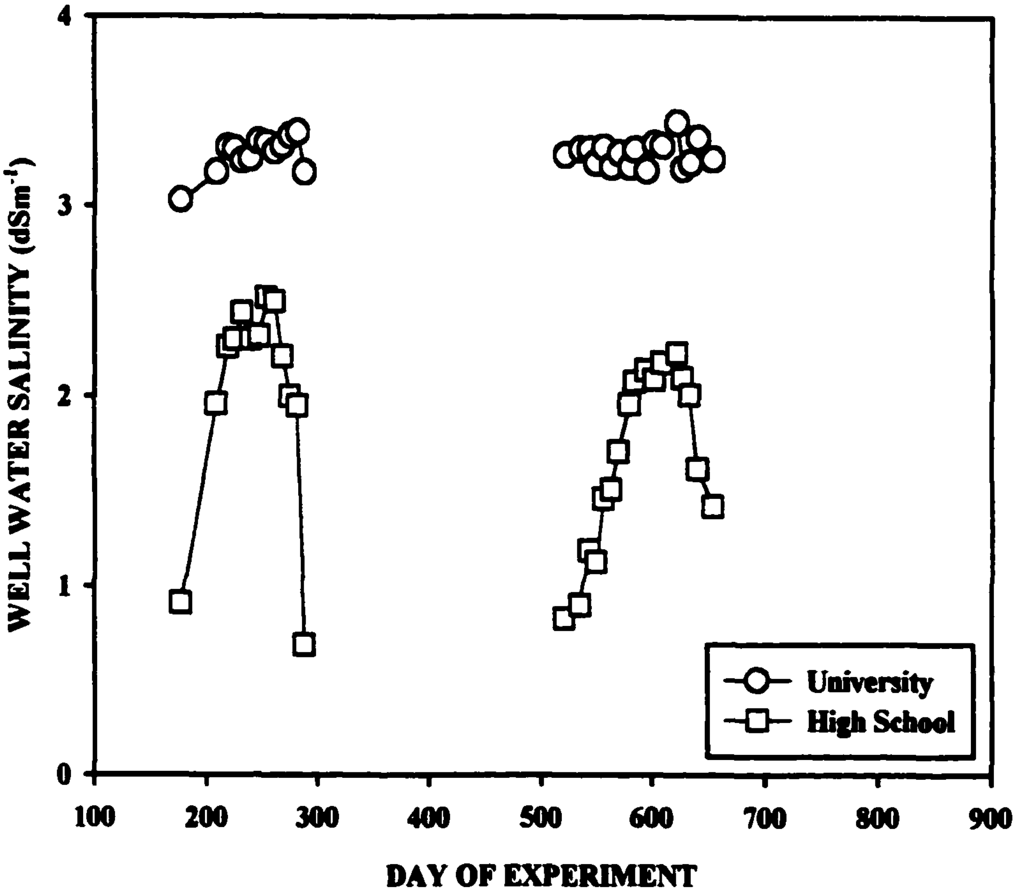

Fig. 2. Well water salinity for both the University site and high school sites for the experimental period May 15, 1997 - May 15, 1999

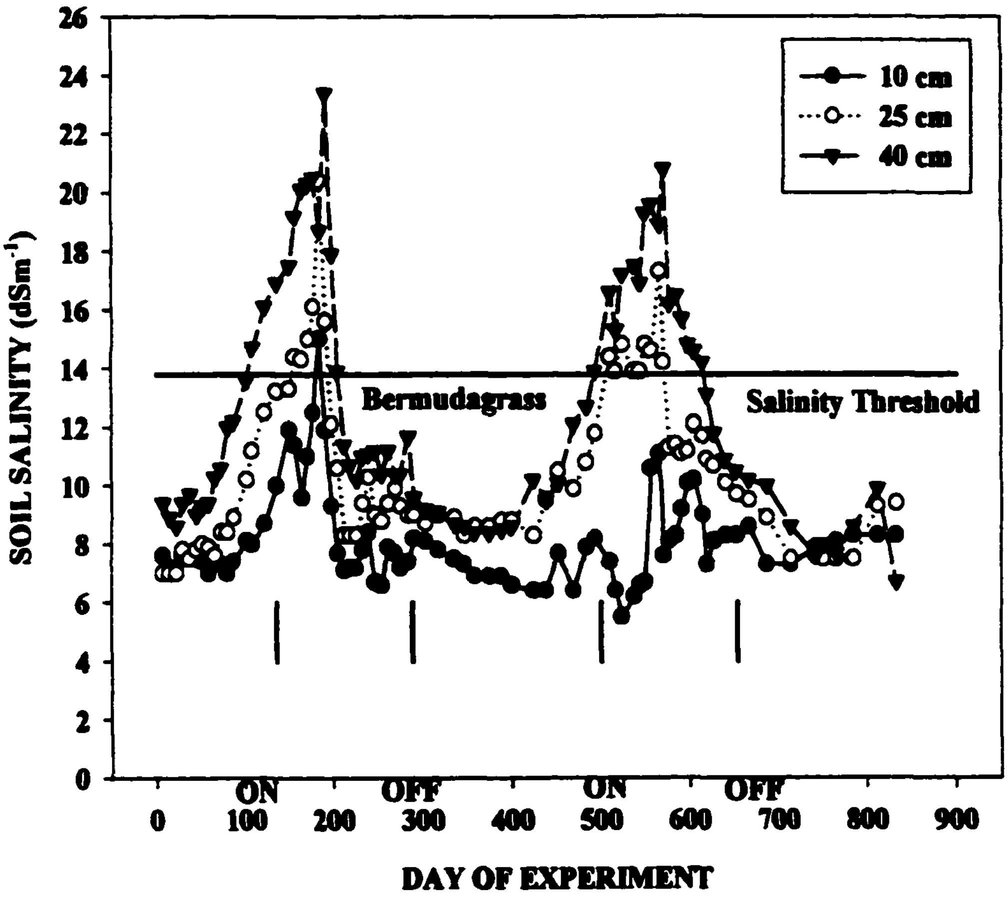

Fig. 3. Average salinity sensor values for the 1 out of 7 saline substitution treatment at the University site for the experimental period May 15, 1997 - May 15, 1999

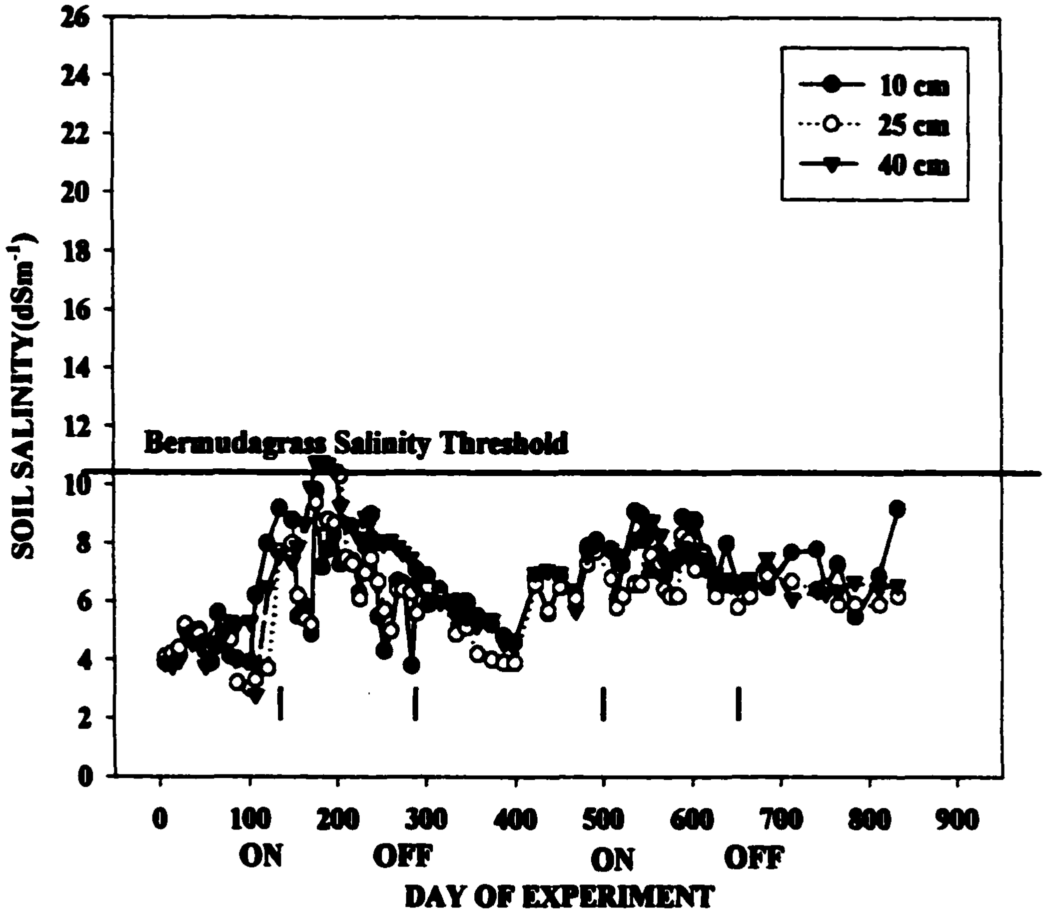

Fig. 4. Average salinity sensor values for the 2 out of 7 saline substitution treatment at the University site for the experimental period May 15, 1997 - May 15, 1999

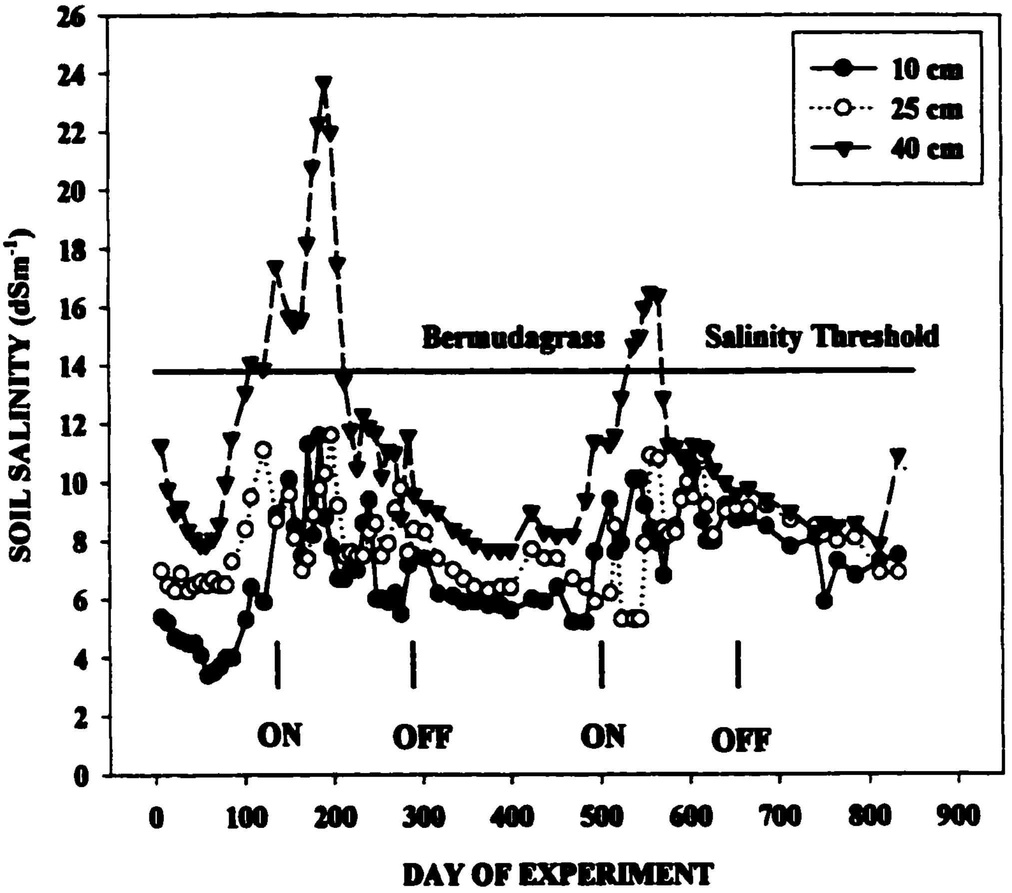

Fig. 5. Average salinity sensor values for the 3 out of 7 saline substitution treatment at the University site for the experimental period May 15, 1997 - May 15, 1999

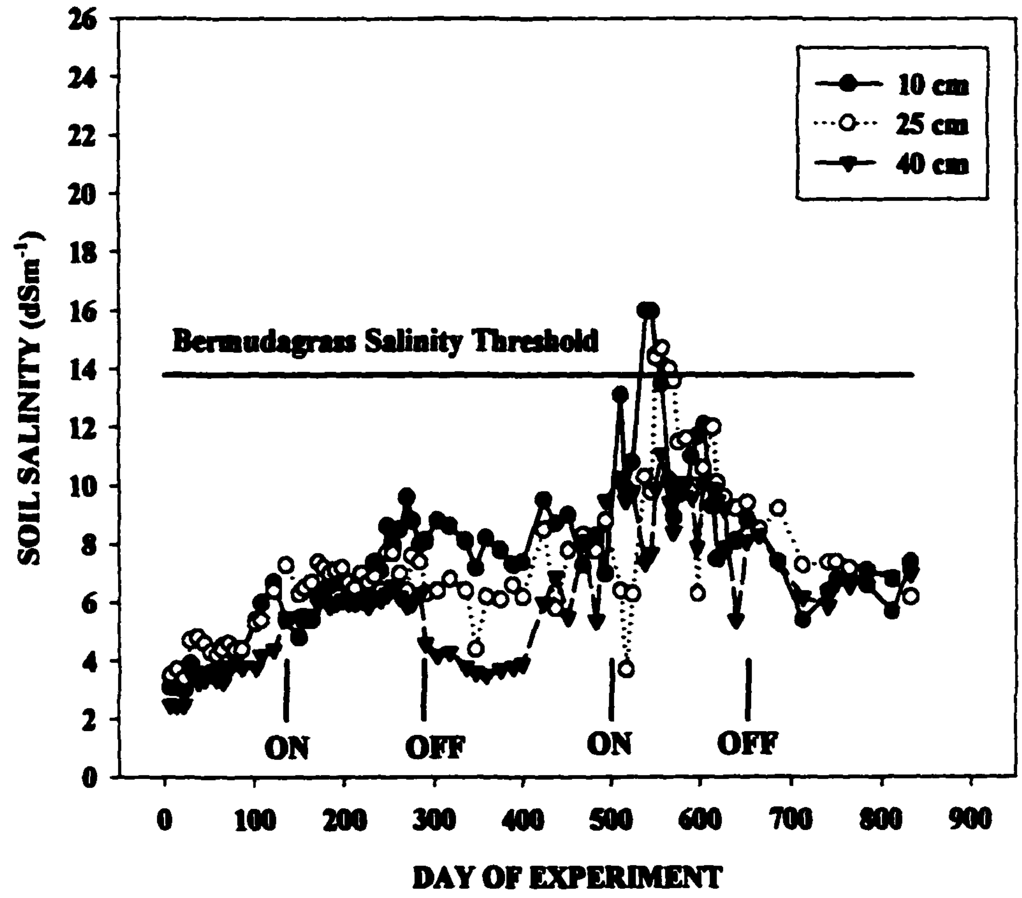

Fig. 6. Average salinity sensor values for the 4 out of 7 saline substitution treatment at the University site for the experimental period May 15, 1997 - May 15, 1999

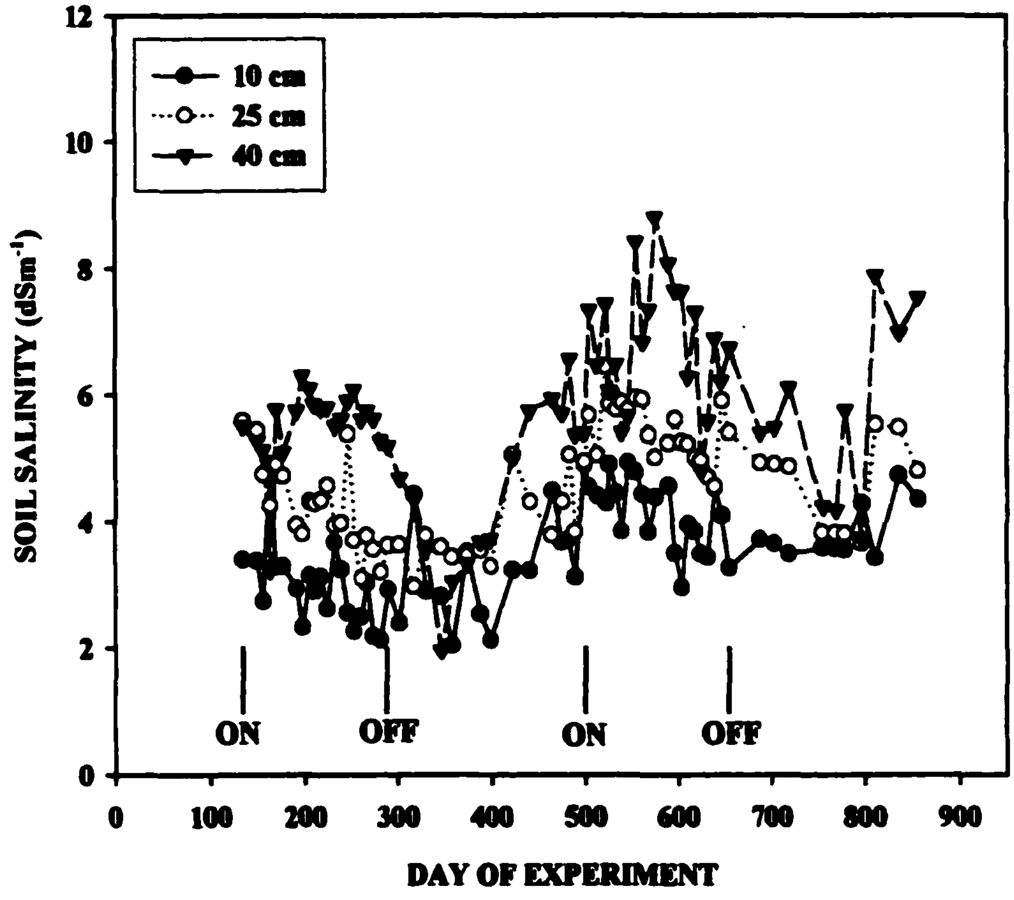

Fig. 7. Average salinity sensor values for the 1 out of 7 saline substitution treatment at the high school site for the experimental period May 15, 1997 - May 15, 1999

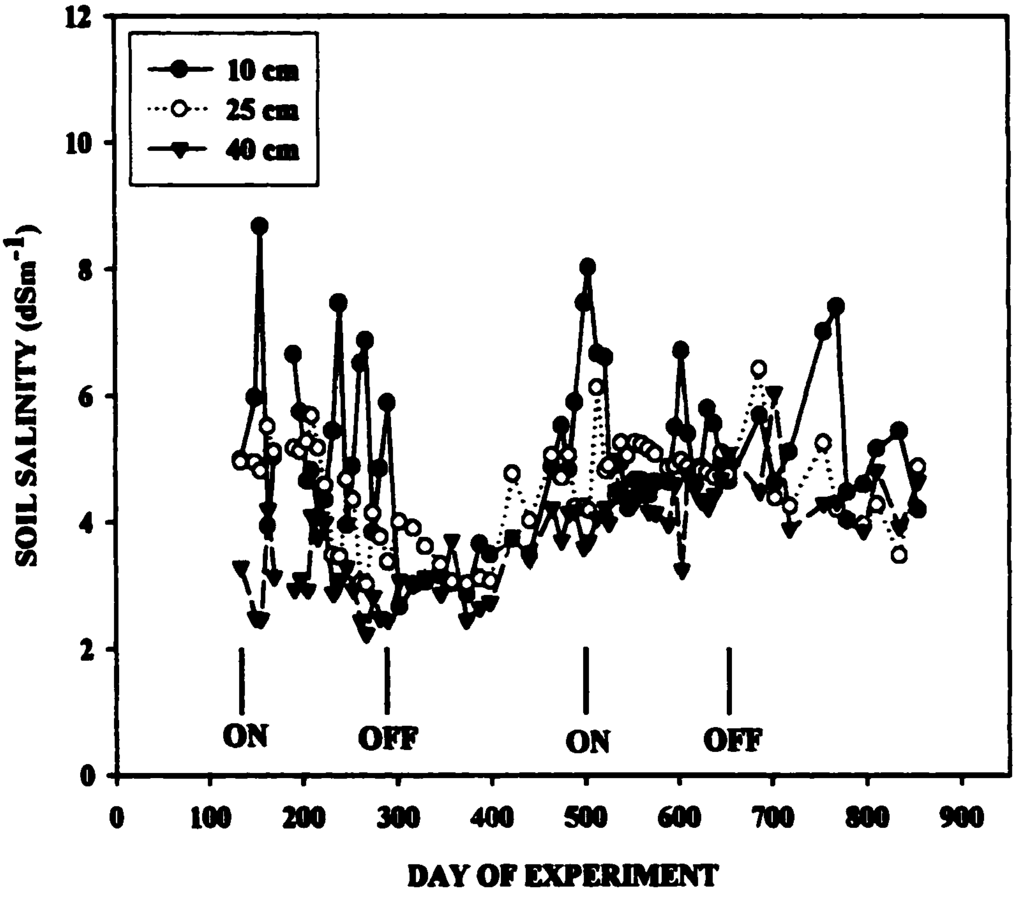

Fig. 8. Average salinity sensor values for the 2 out of 7 saline substitution treatment at the high school site for the experimental period May 15, 1997 - May 15, 1999

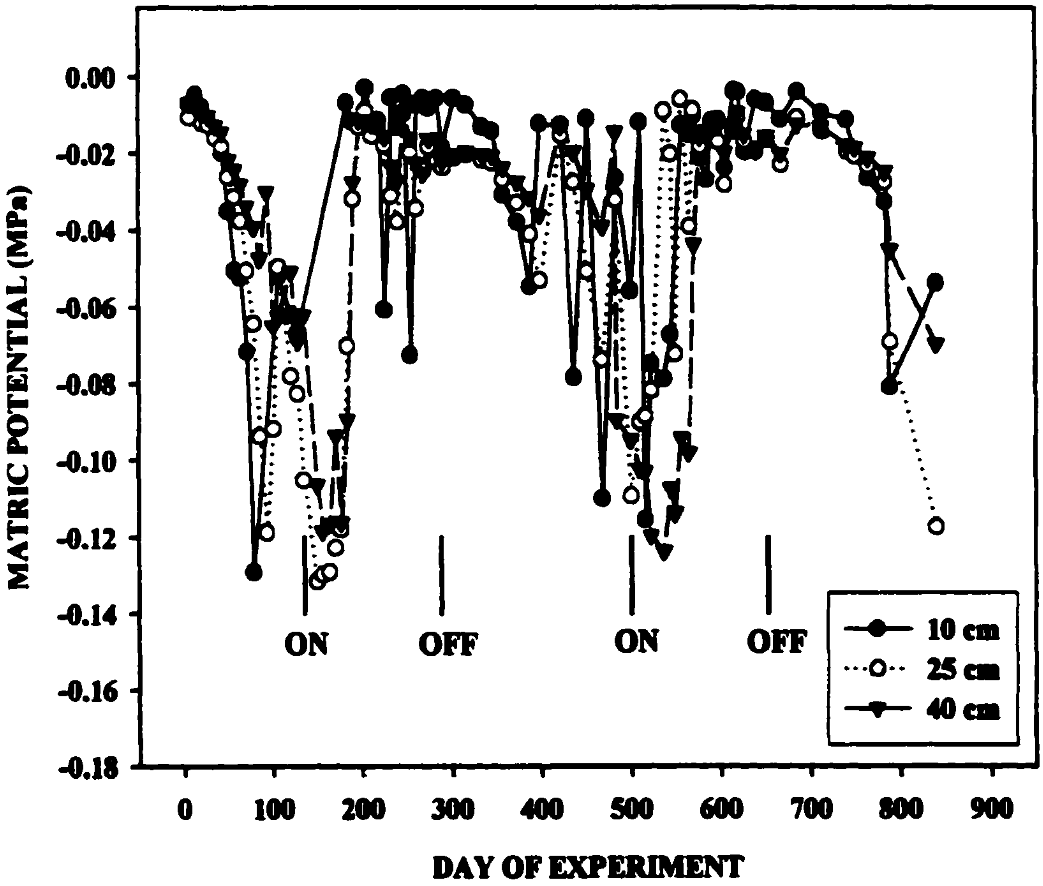

Fig. 9. Average matric potential values for the 1 out of 7 saline substitution treatment at the University site for the experimental period May 15, 1997 - May 15, 1999

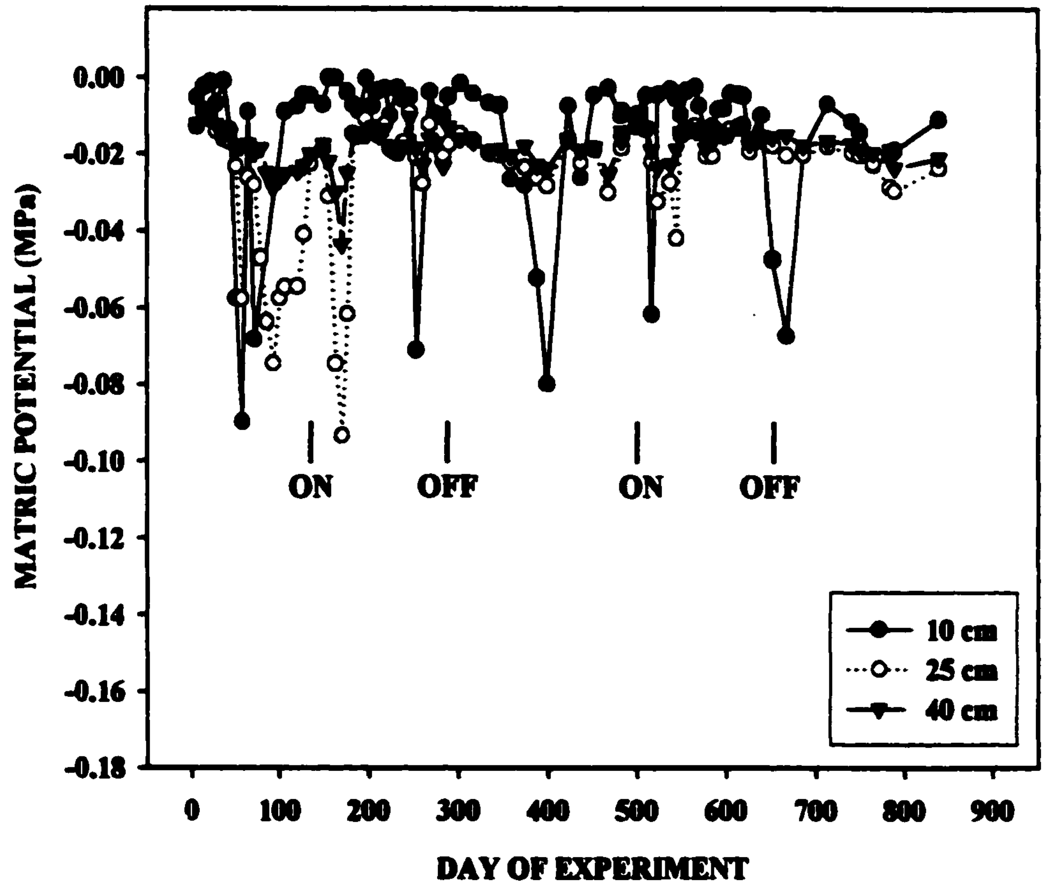

Fig. 10. Average matric potential values for the 2 out of 7 saline substitution treatment at the University site for the experimental period May 15, 1997 - May 15, 1999

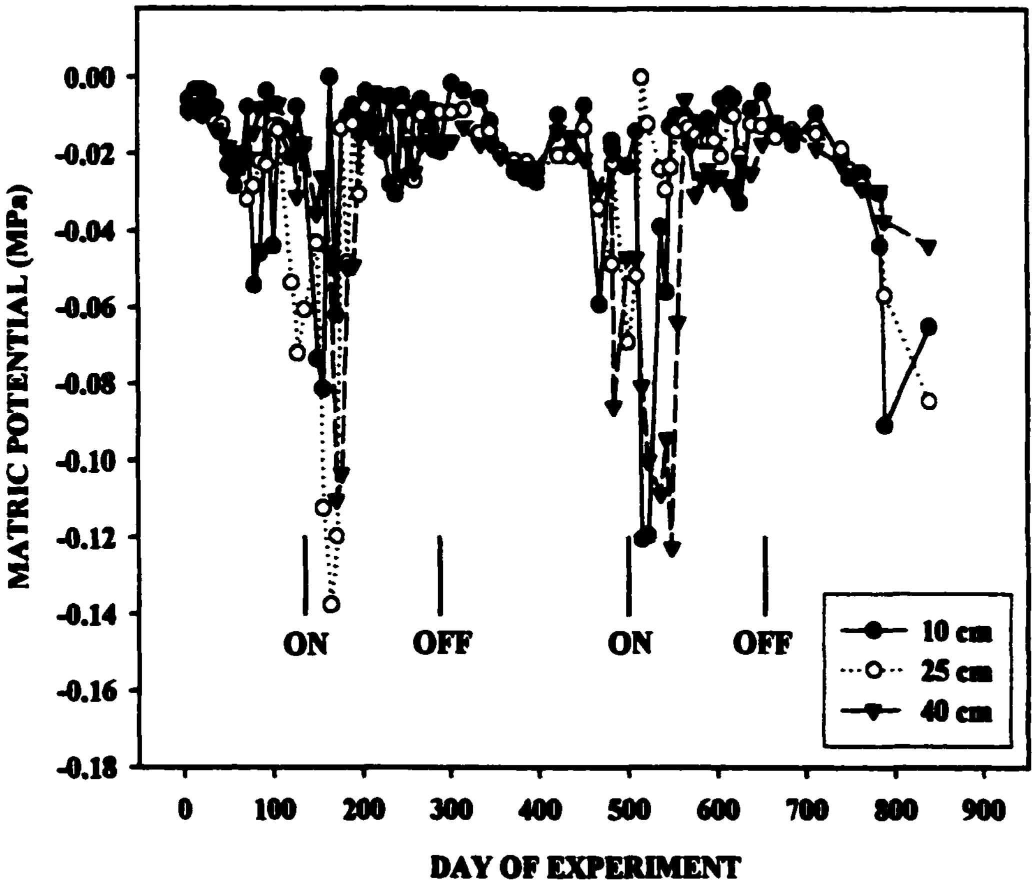

Fig. 11. Average matric potential values for the 3 out of 7 saline substitution treatment at the University site for the experimental period May 15, 1997 - May 15, 1999

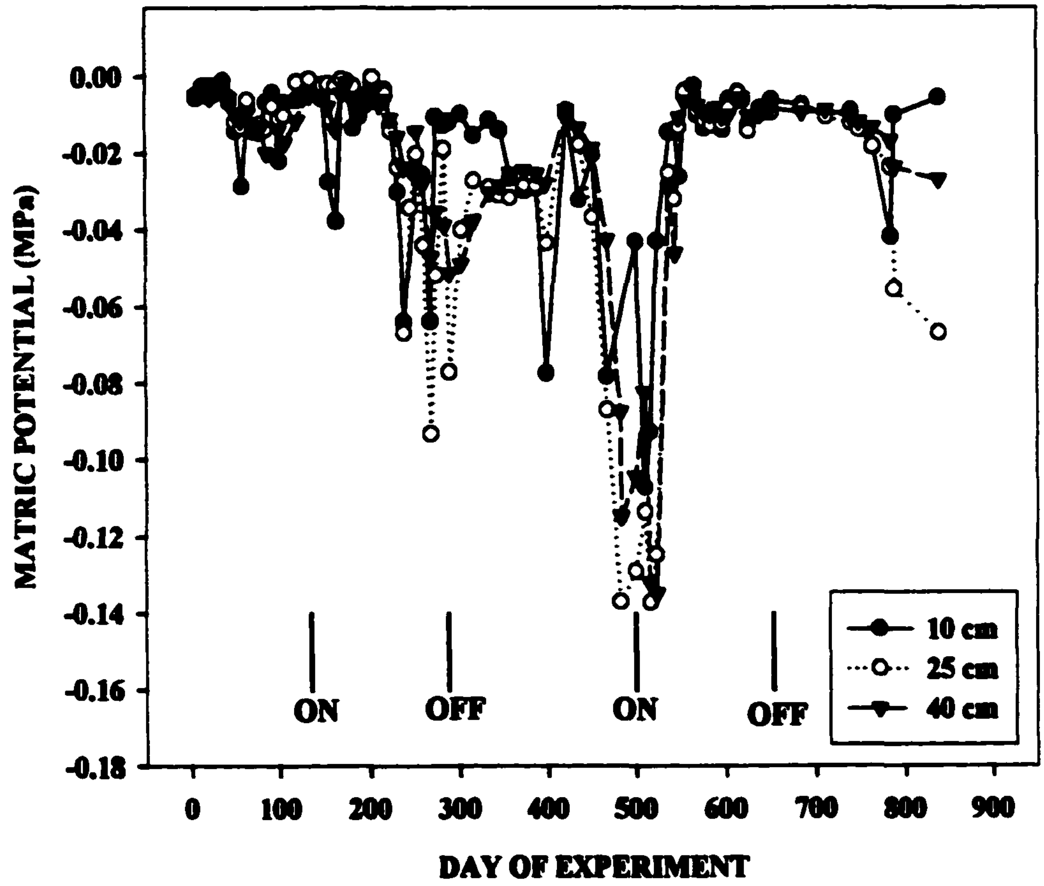

Fig. 12. Average matric potential values for the 4 out of 7 saline substitution treatment at the University site for the experimental period May 15, 1997 - May 15, 1999

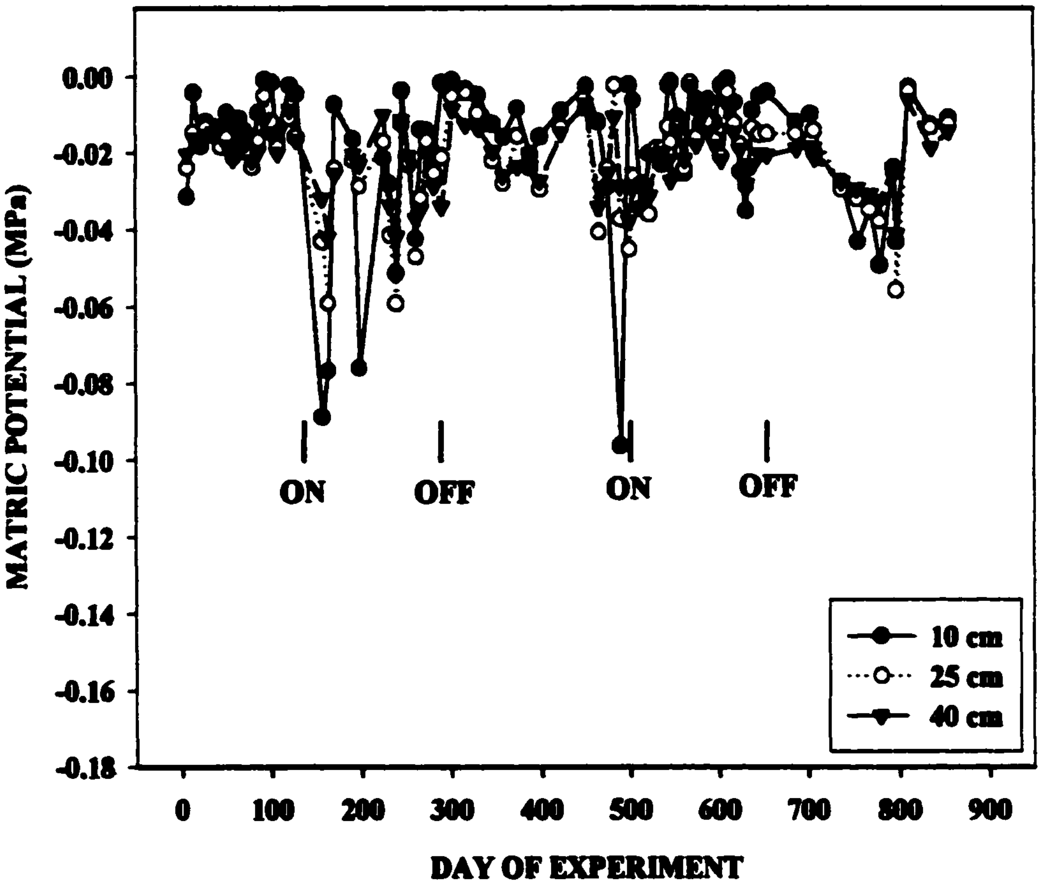

Fig. 13. Average matric potential values for the 1 out of 7 saline substitution treatment at the high school site for the experimental period May 15, 1997 - May 15, 1999

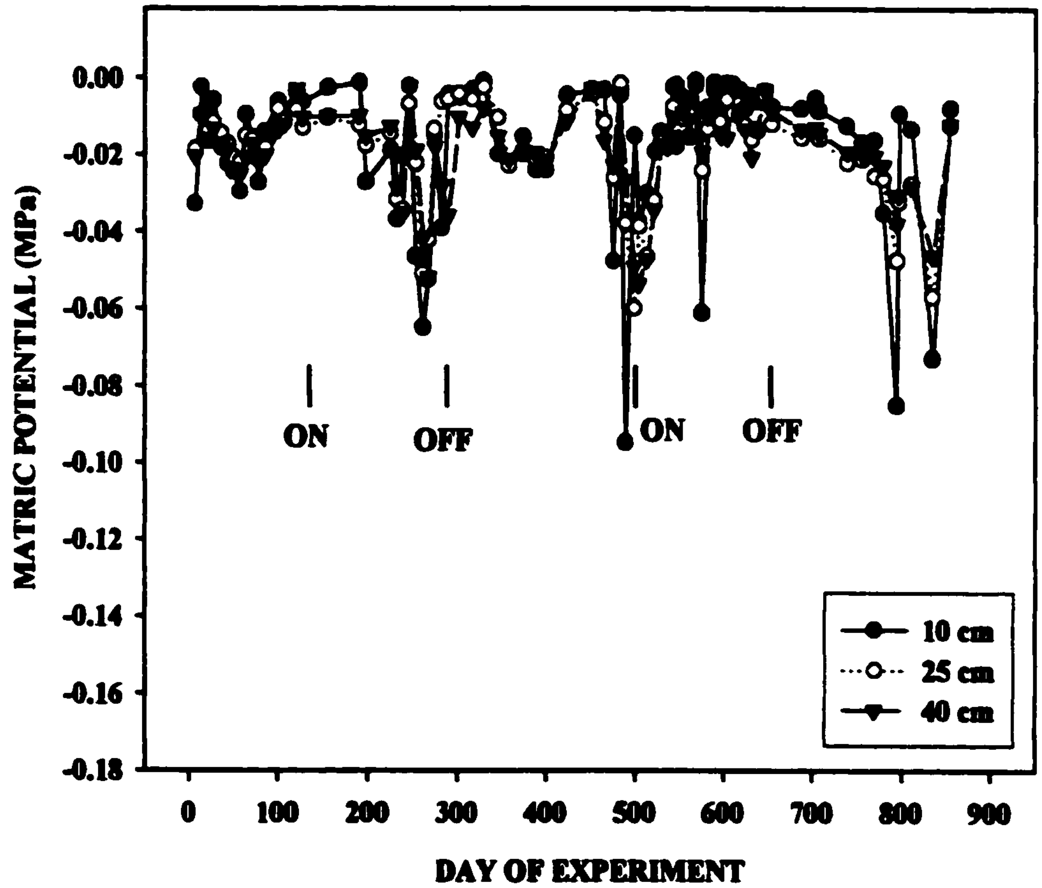

Fig. 14. Average matric potential values for the 2 out of 7 saline substitution treatment at the high school site for the experimental period May 15, 1997 - May 15, 1999

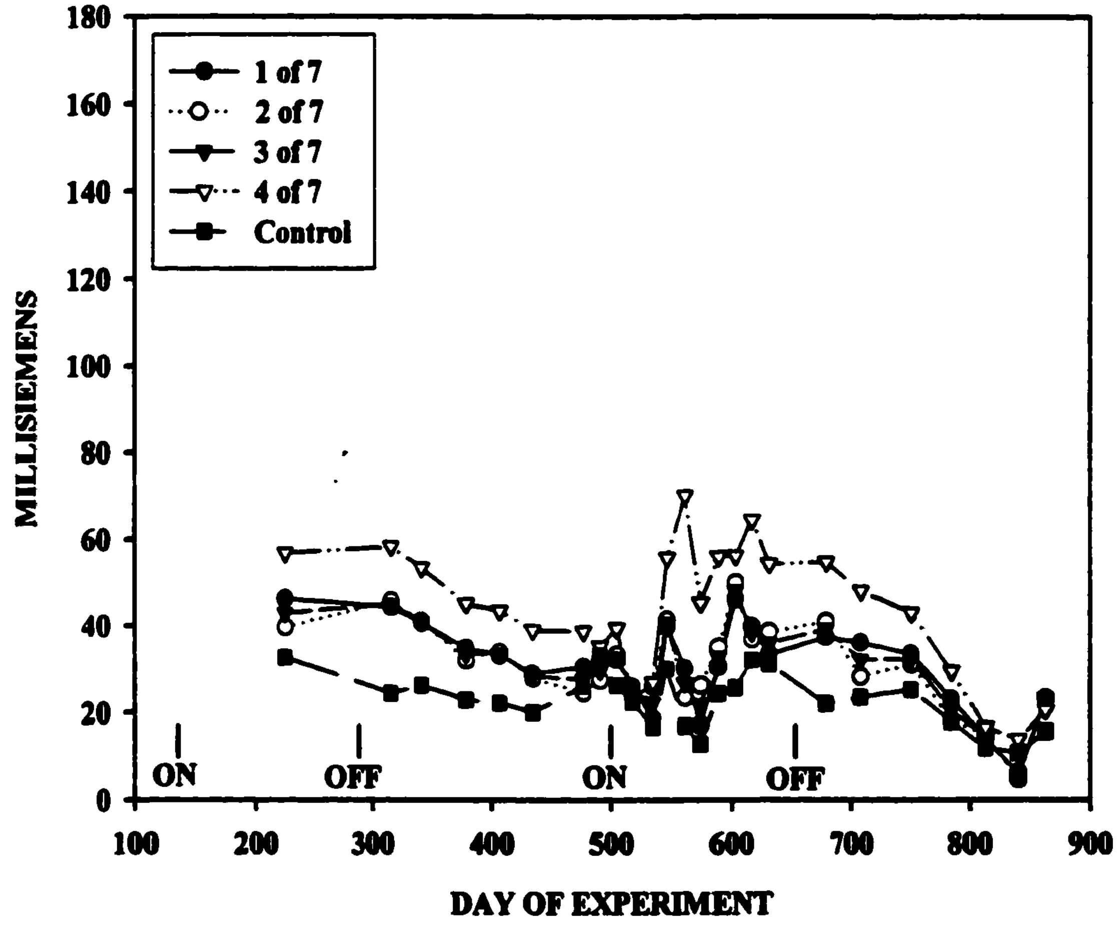

Fig. 15. Average horizontally adjusted EM 38 values for all treatments at the University site for the experimental period May 15, 1997 - May 15, 1999

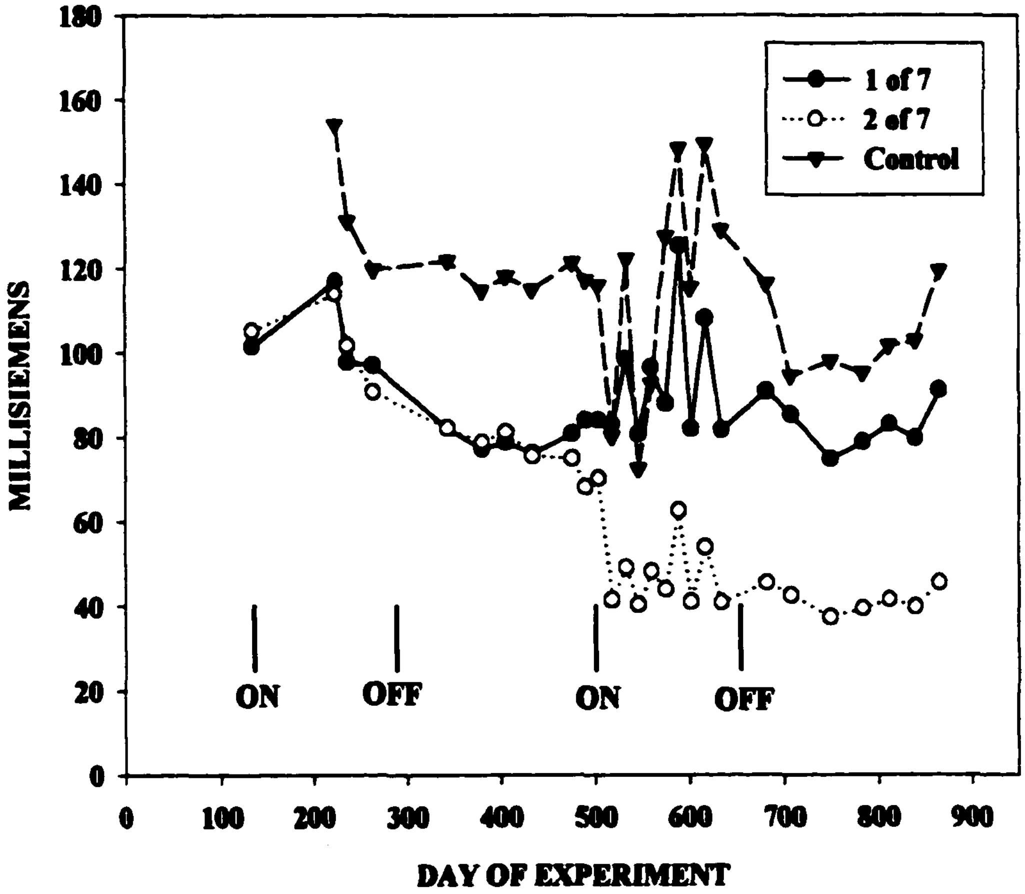

Fig. 16. Average horizontally adjusted EM 38 values for all treatments at the high school site for the experimental period May 15, 1997 - May 15, 1999

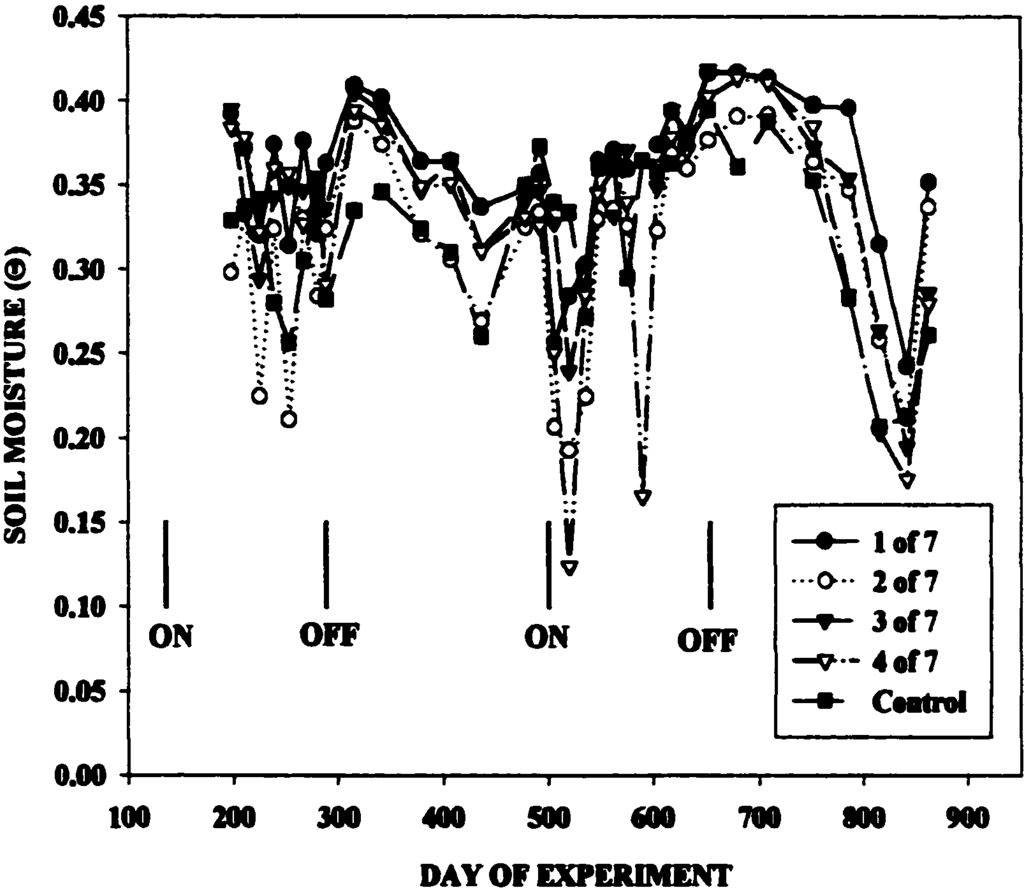

Fig. 17. Average soil moisture (theta probe) for all treatments at the University site for the experimental period May 15, 1997 - May 15, 1999

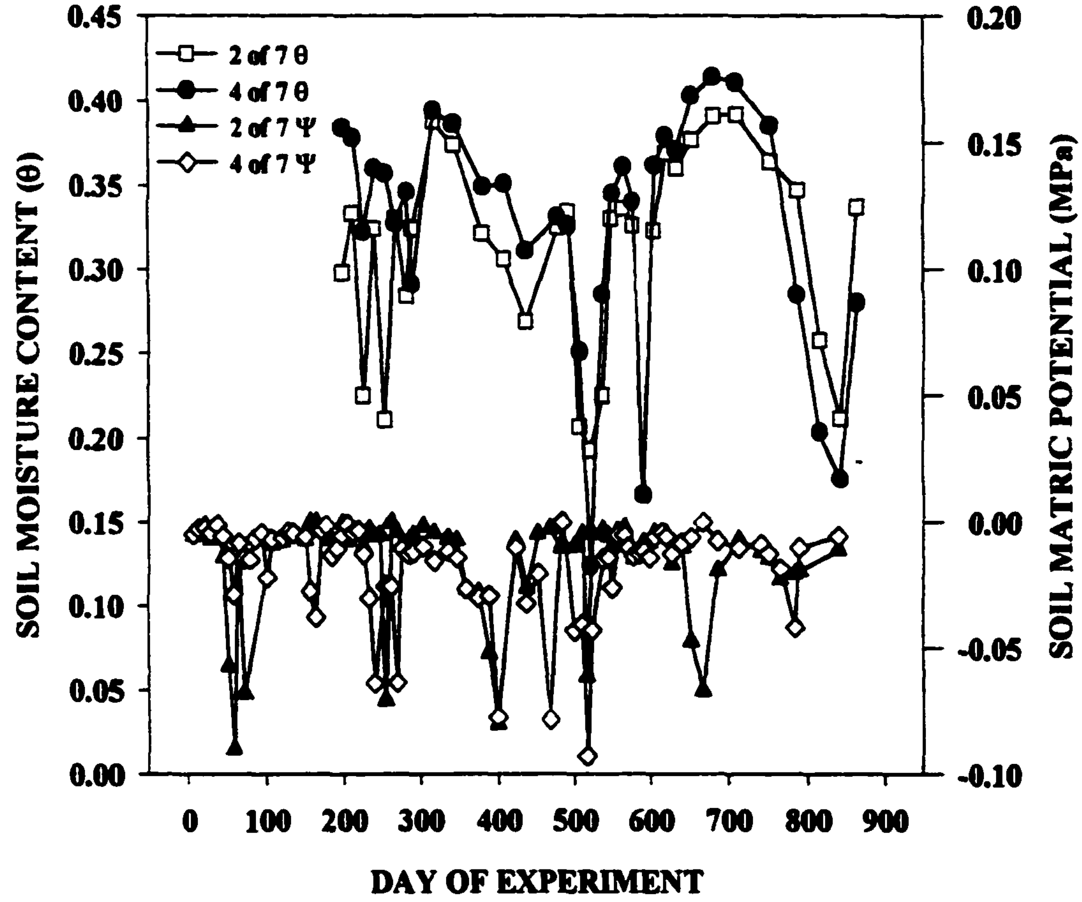

Fig. 18. Comparison of 10 cm matric potentials and soil moisture content (theta probe) for the 2 and 4 out of 7 saline irrigation substitution treatments at the University site for the experimental period May 15, 1997 - May 15, 1999

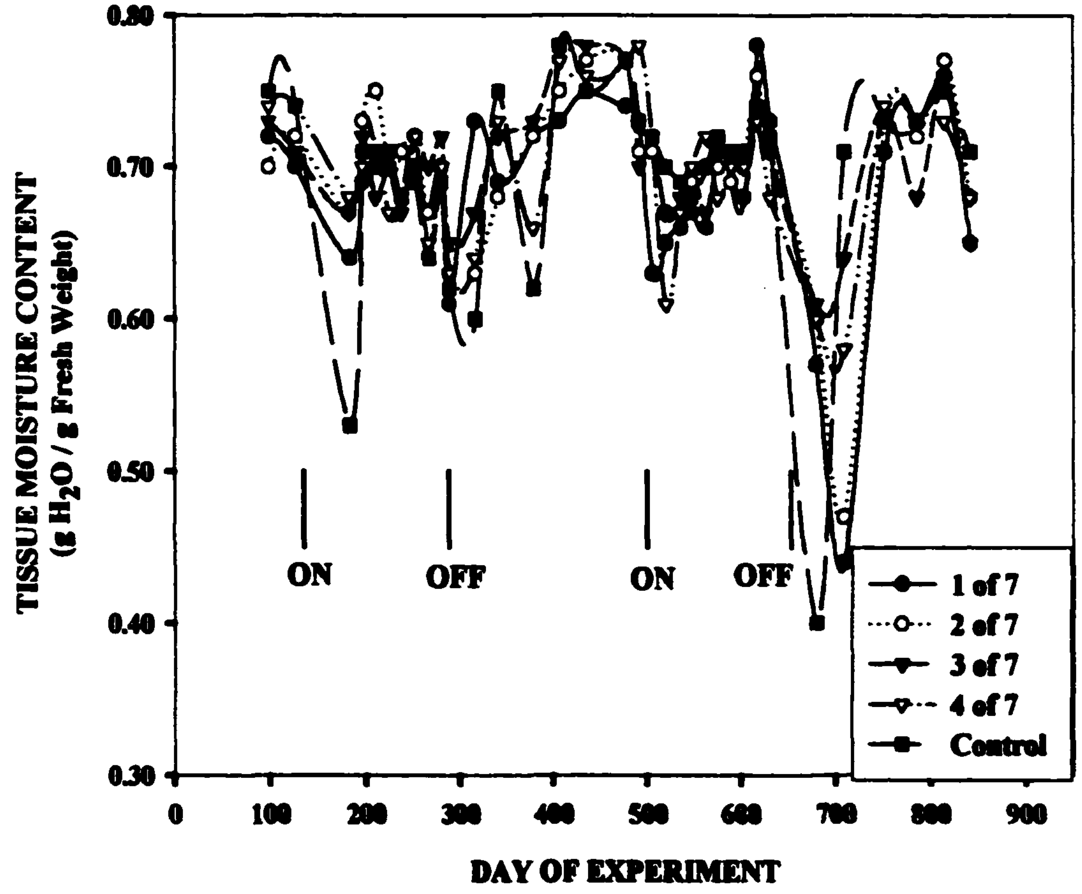

Fig. 19. Tissue moisture content for all treatments at the University site for the experimental period May 15, 1997 - May 15, 1999

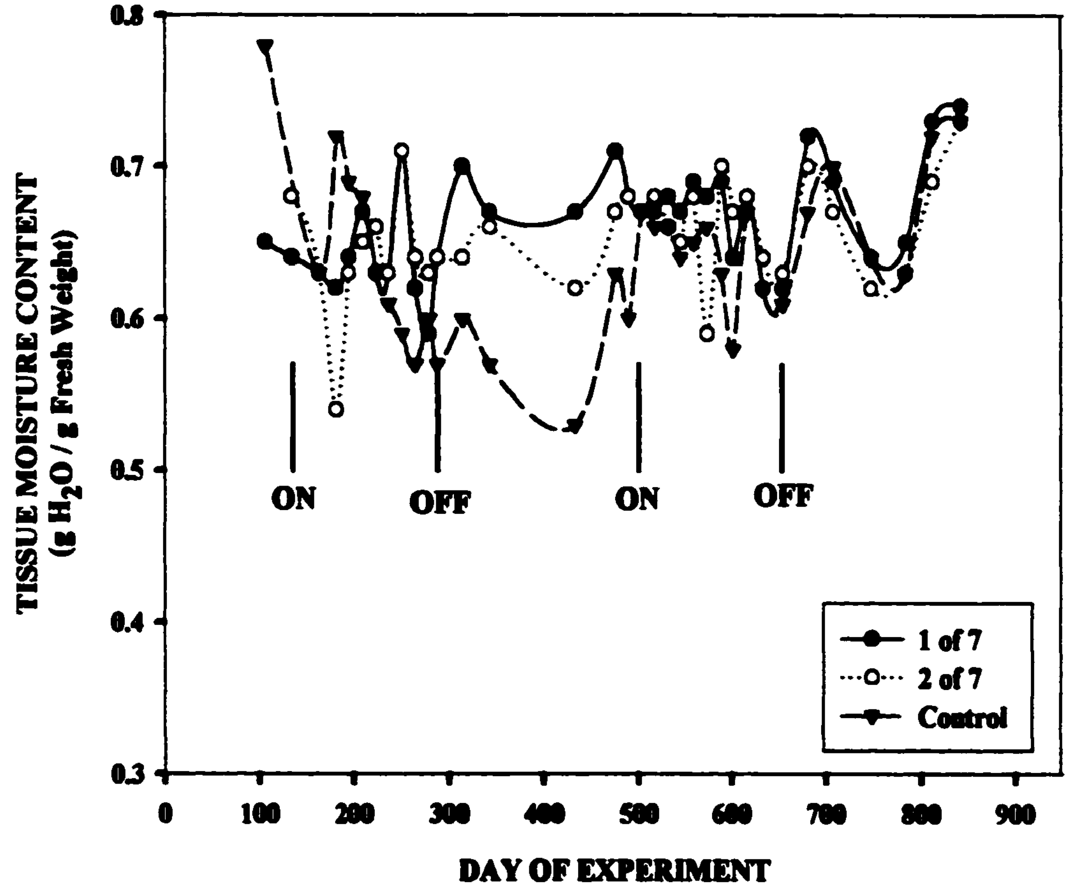

Fig. 20. Tissue moisture content for all treatments at the high school site for the experimental period May 15, 1997 - May 15, 1999

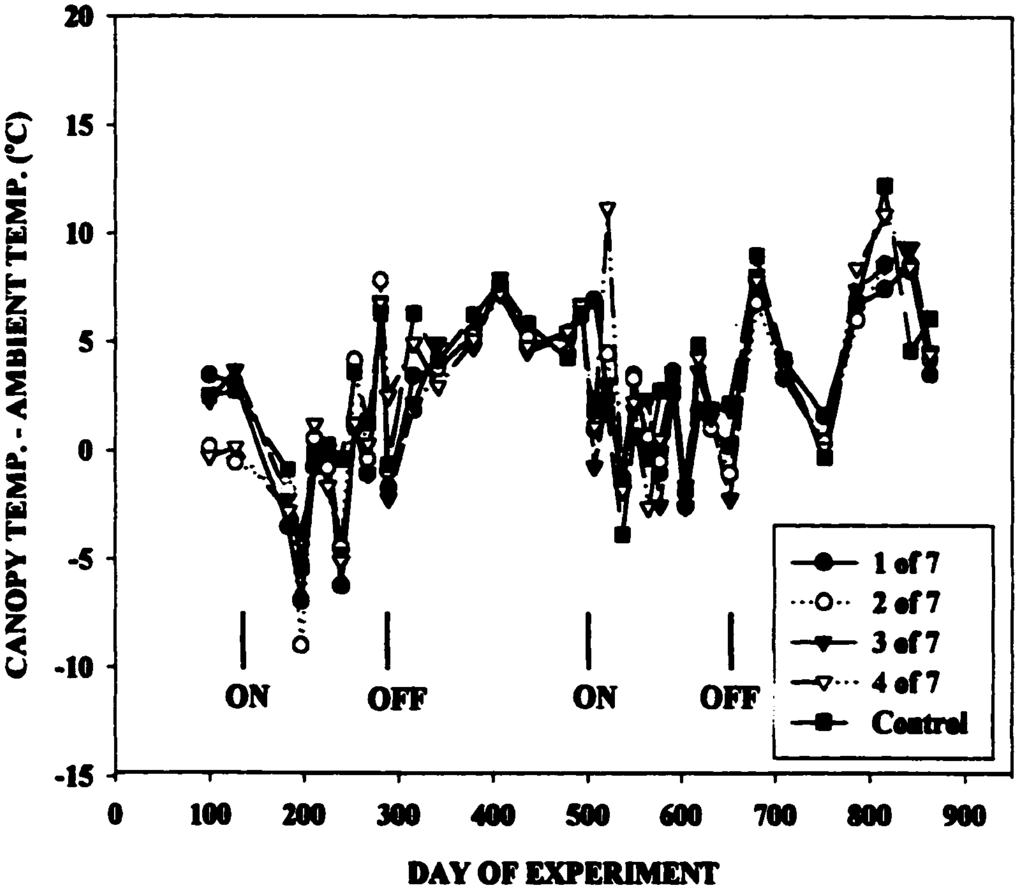

Fig. 21. Average canopy temperature - ambient temperature for all treatments at the University site for the experimental period May 15, 1997 - May 15, 1999

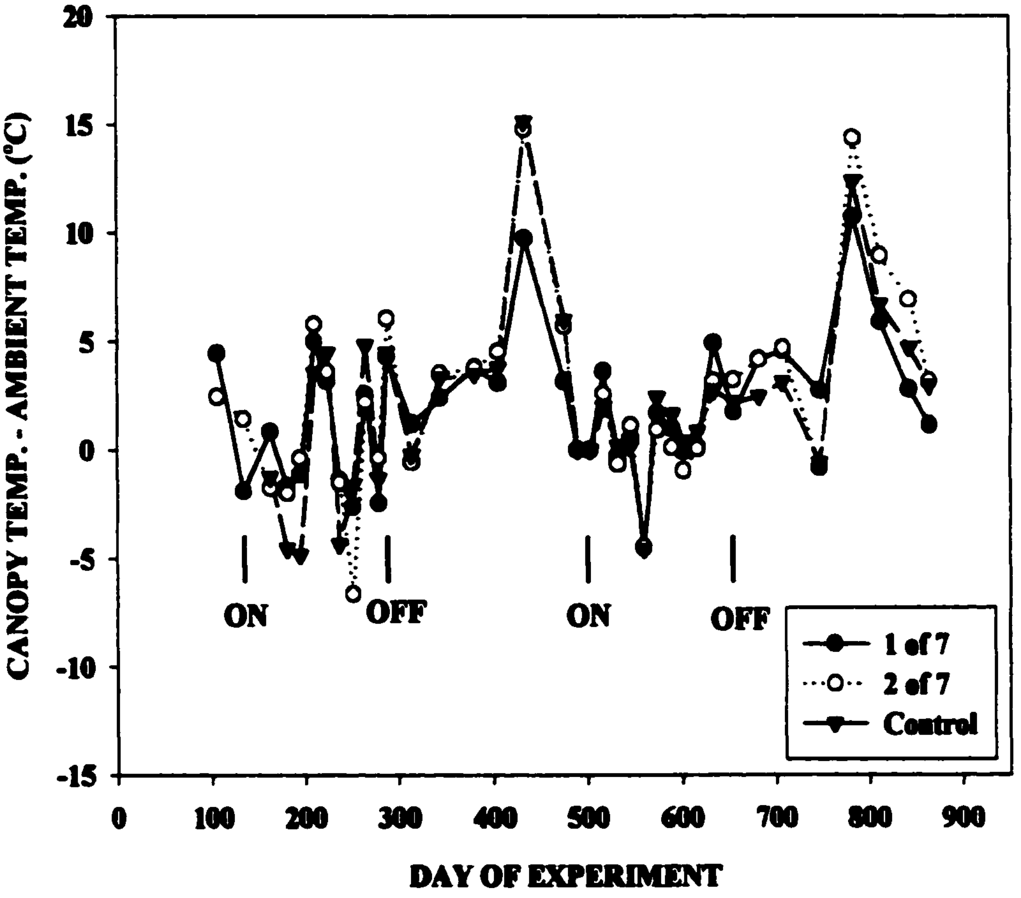

Fig. 22. Average canopy temperature - ambient temperature for all treatments at the high school site for the experimental period
May 15, 1997 - May 15, 1999

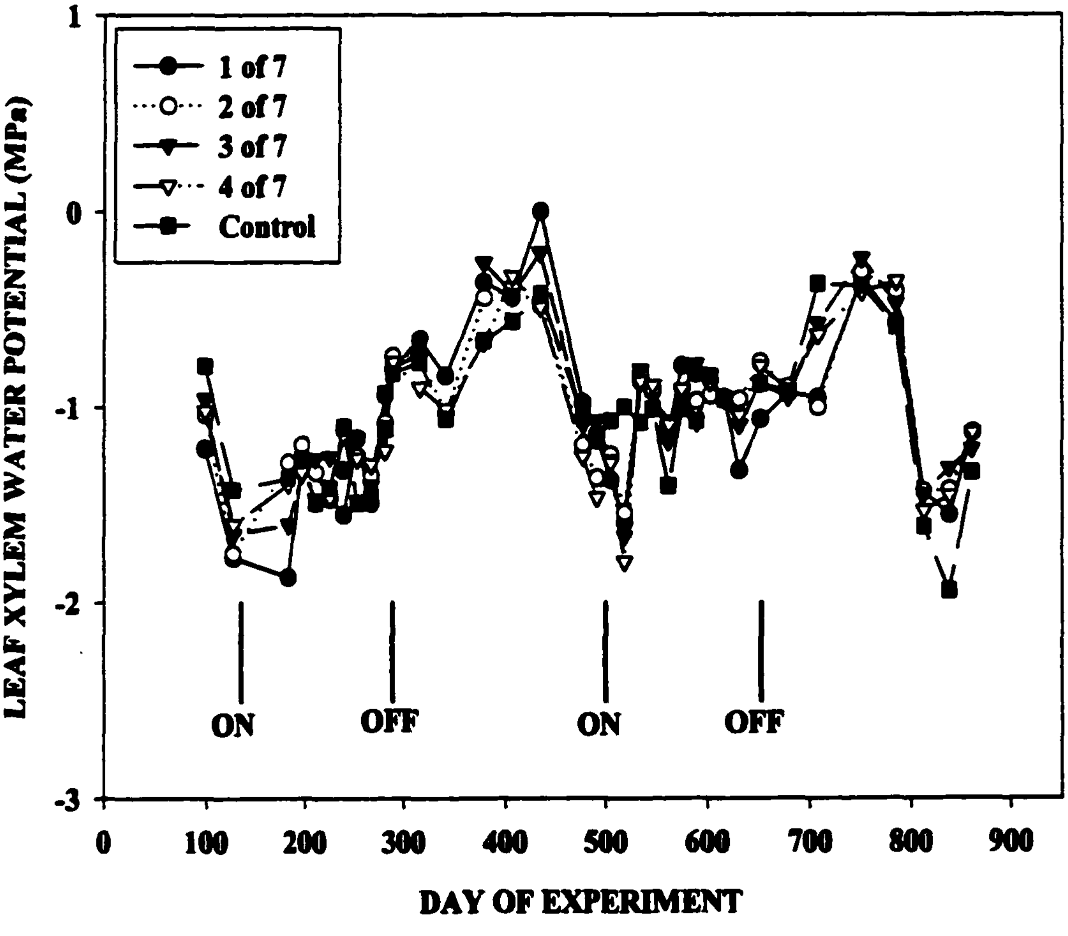

Fig. 23. Average midday leaf xylem water potential for all treatments at the University site for the experimental period May 15, 1997 - May 15, 1999

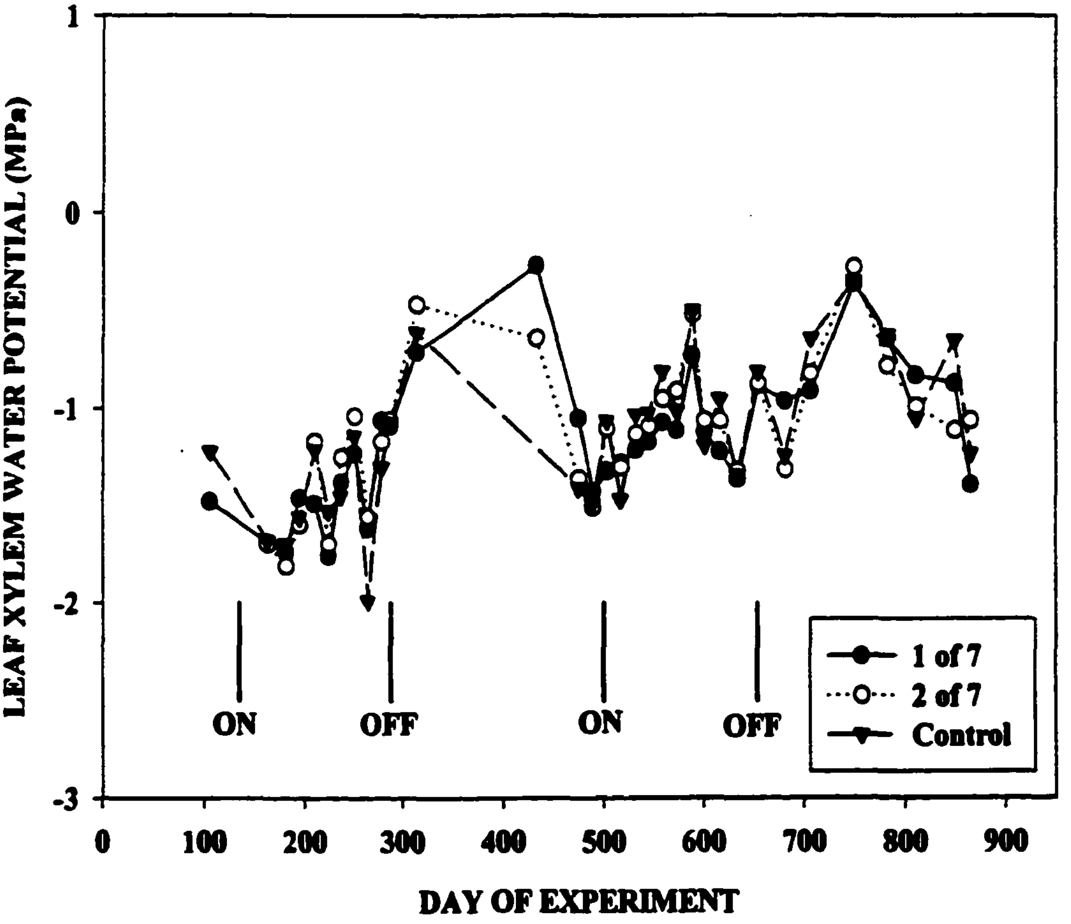

Fig. 24. Average midday leaf xylem water potential for all treatments at the high school site for the experimental period May 15, 1997 - May 15, 1999

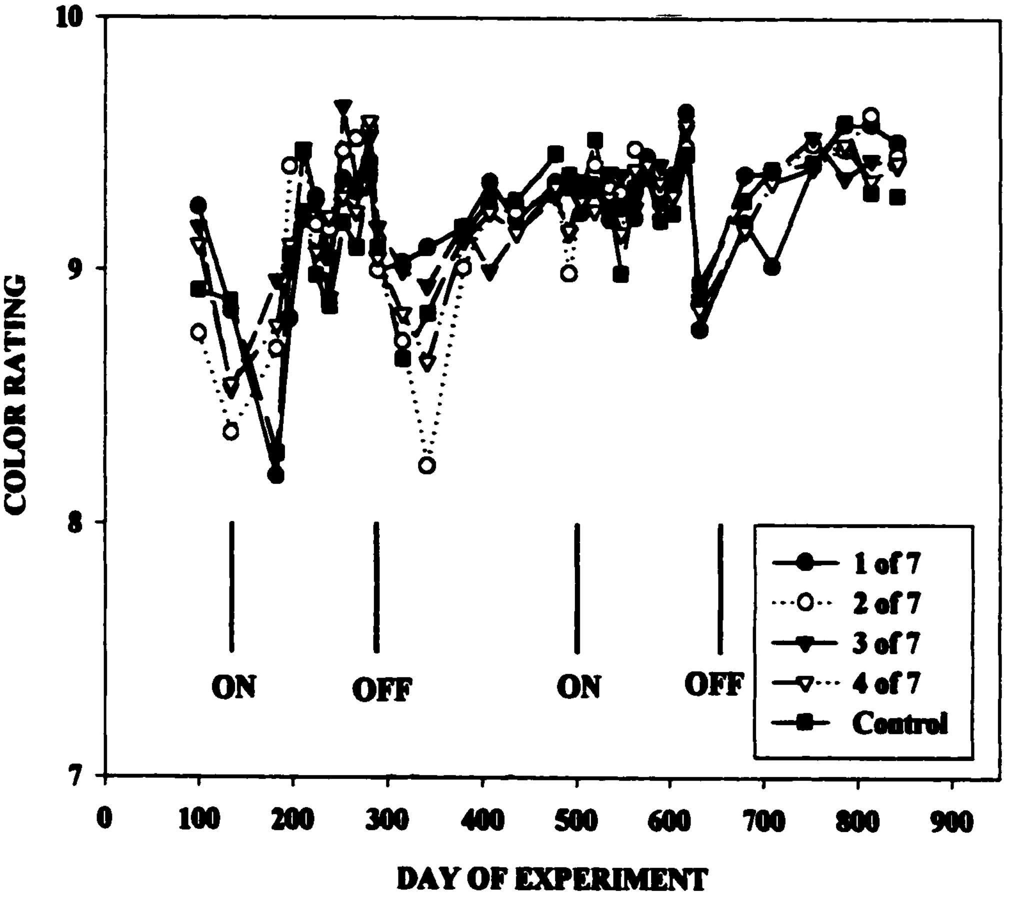

Fig. 25. Average color ratings (0-10) for all treatments at the University site for the experimental period May 15, 1997 - May 15, 1999

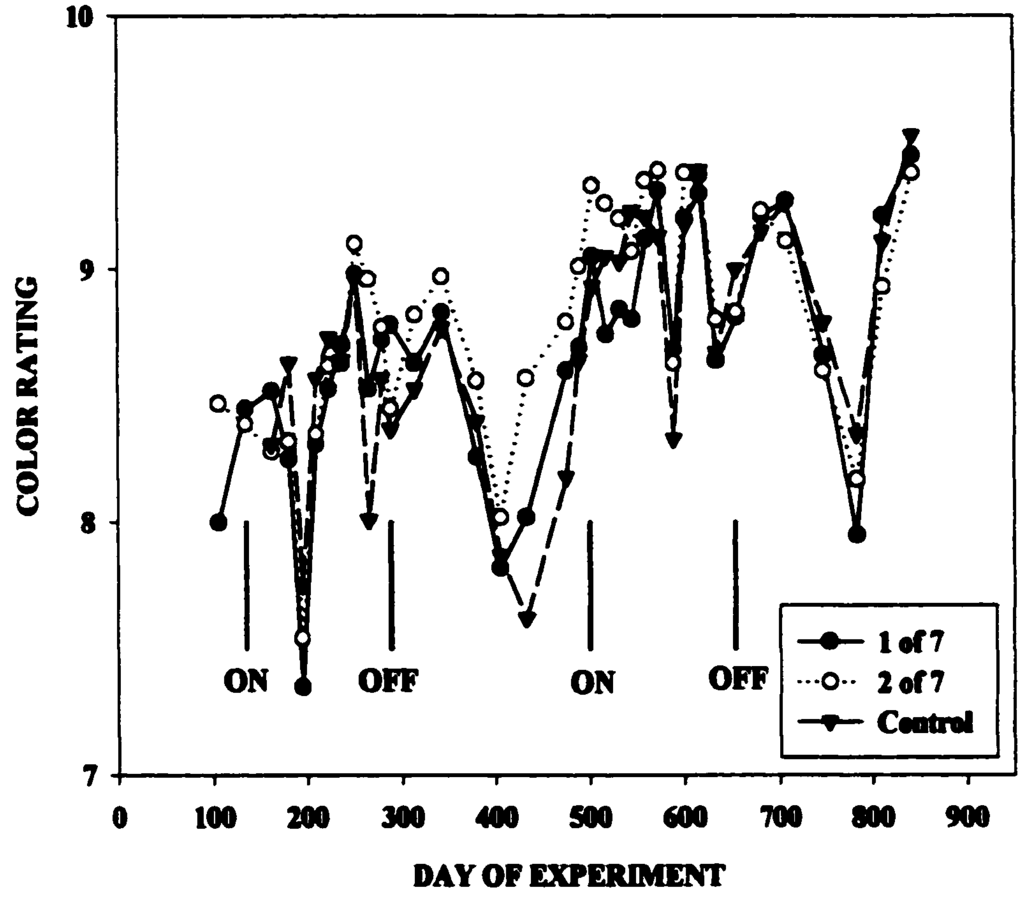

Fig. 26. Average color ratings for all treatments at the high school site for the experimental period May 15, 1997 - May 1999

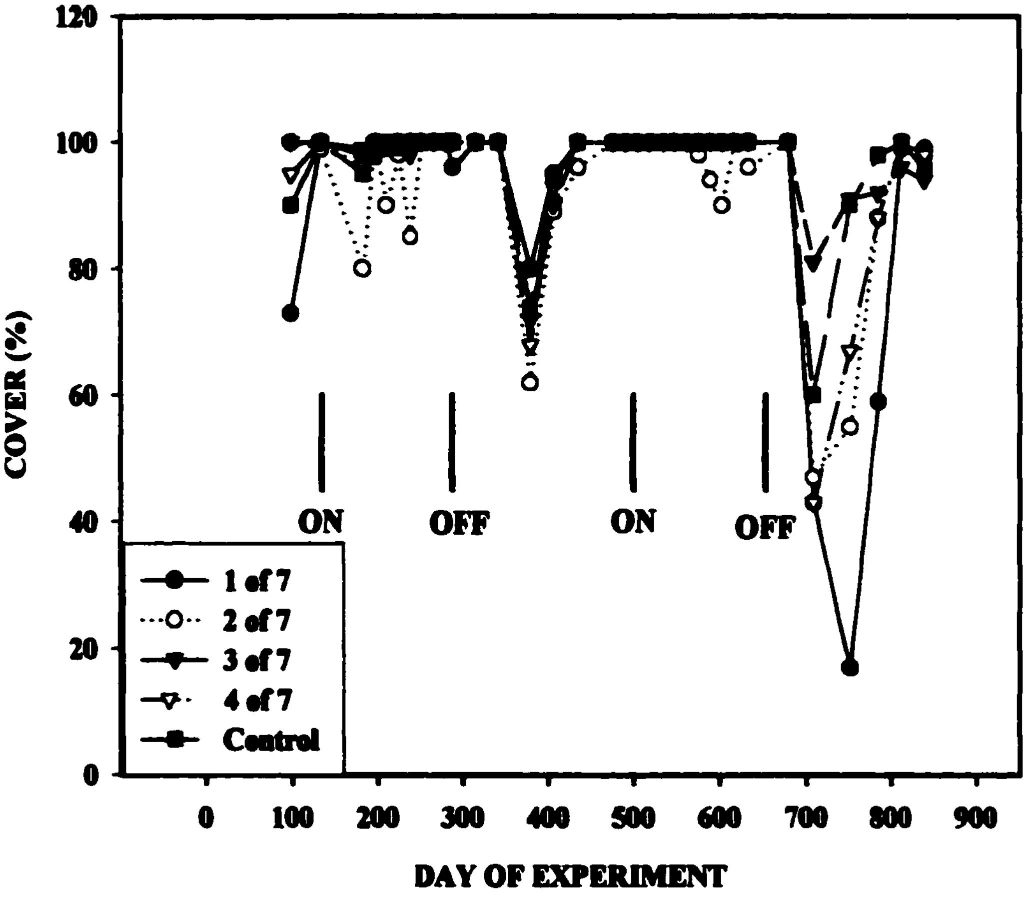

Fig. 27. Average cover percentages for all treatments at the University site for the experimental period May 15, 1997 - May 15, 1999

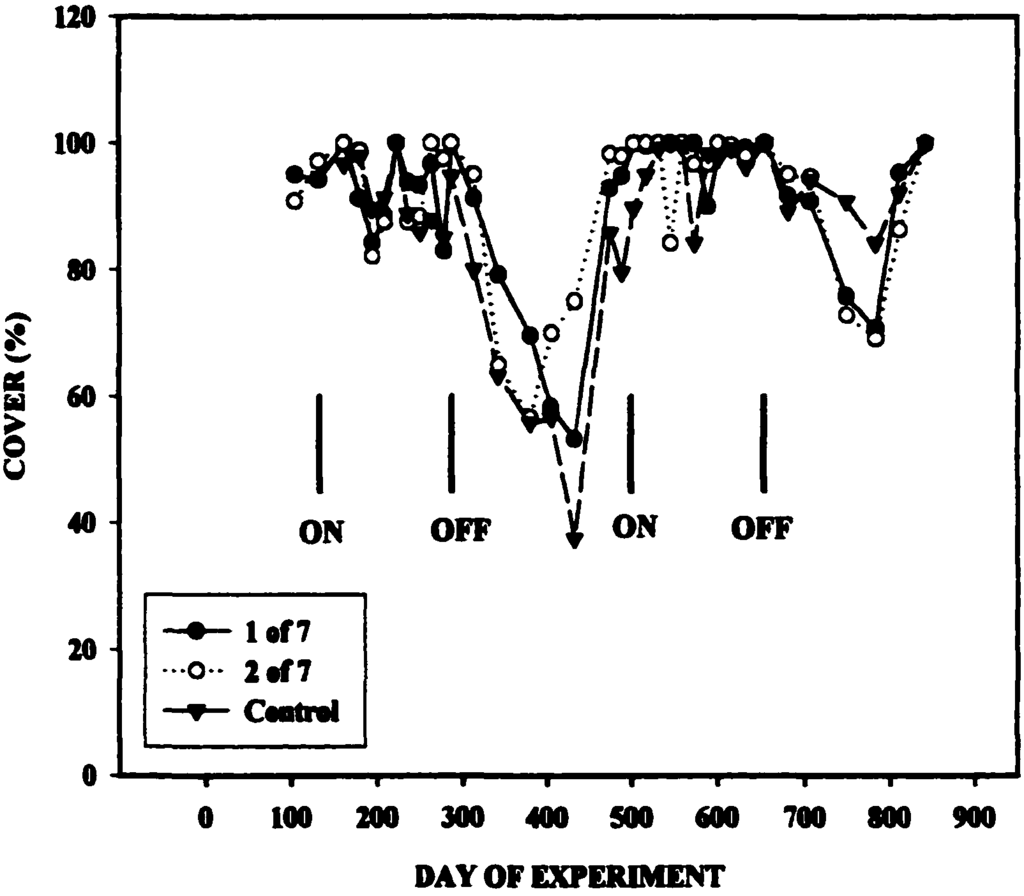

Fig. 28. Average cover percentages for all treatments at the high schools site for the experimental period May 15, 1997 - May 15, 1999

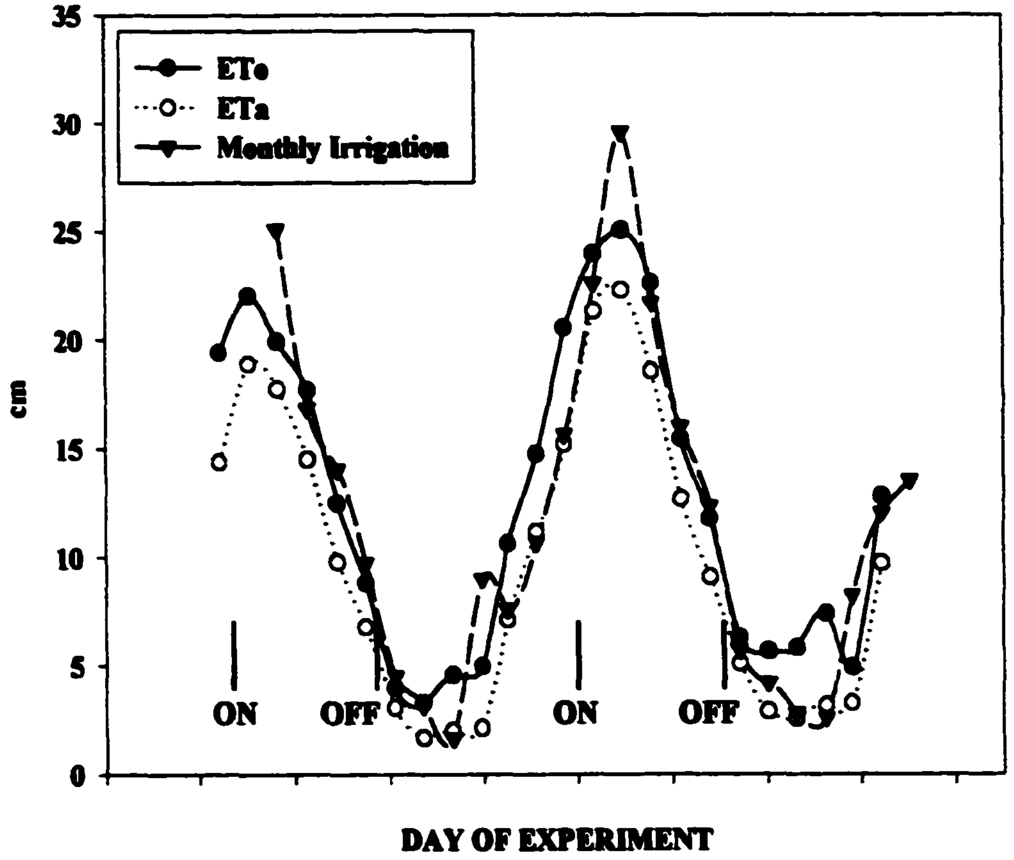

Fig. 29. A comparison of ETa, ETo and monthly irrigation for the 4 out of 7 saline irrigation treatment at the University site for the experimantal period May 15, 1997 to May 15, 1999

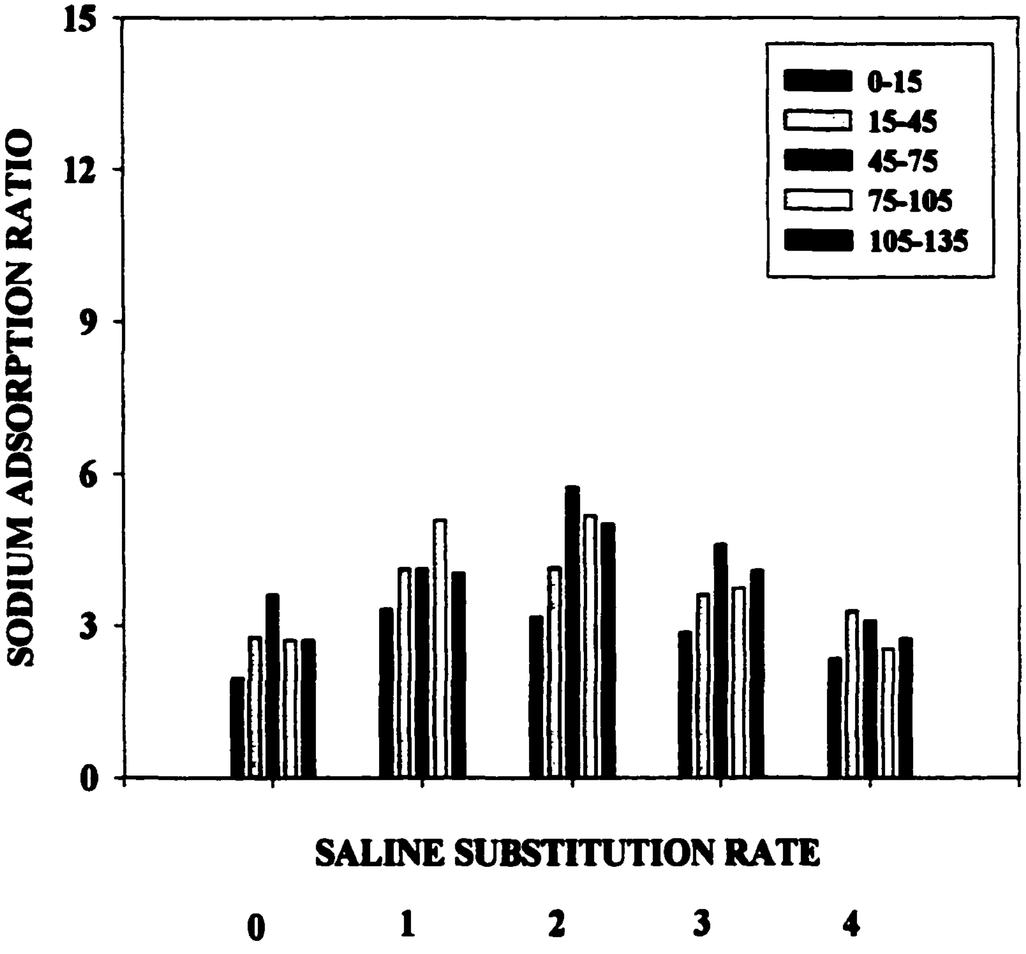

Fig. 30. Sodium adsorption ratios for all sample depths and treatments at the University site for May 1998

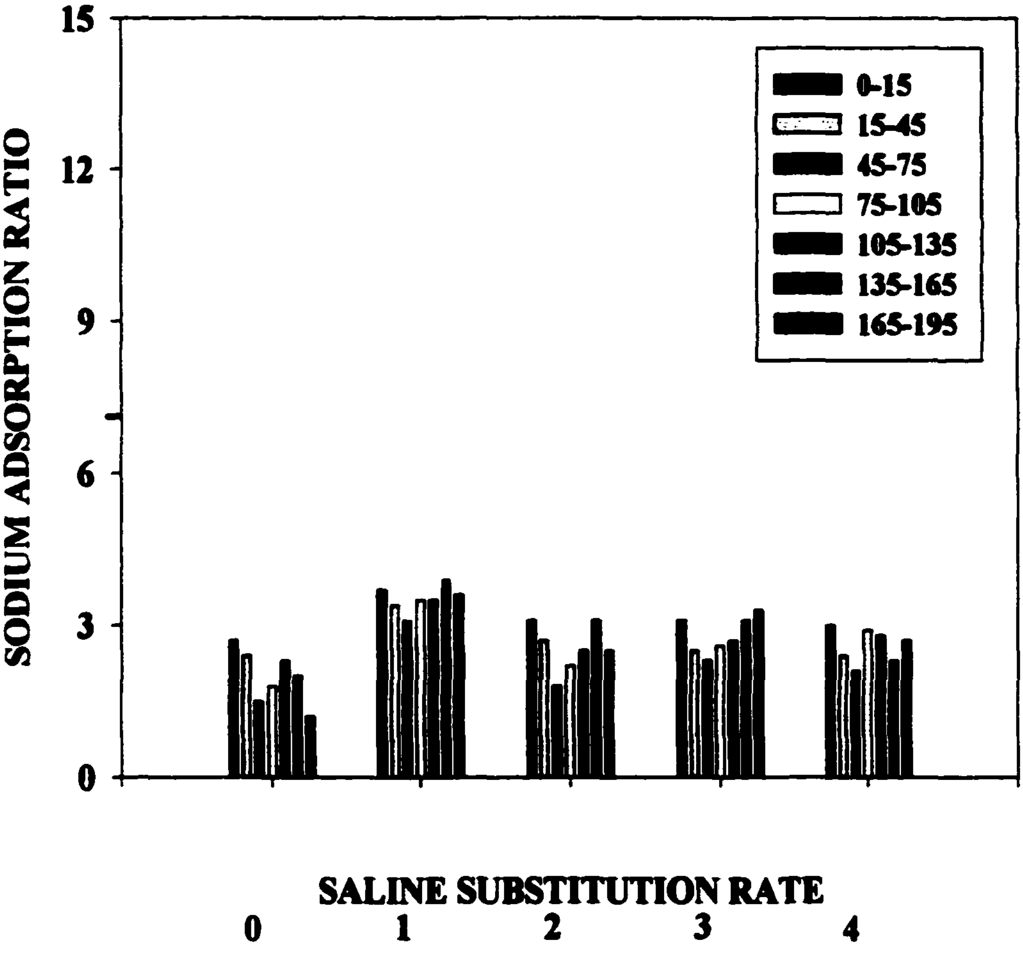

Fig. 31. Sodium adsorption ratios for all sample depths and treatments at the University site for May 1999

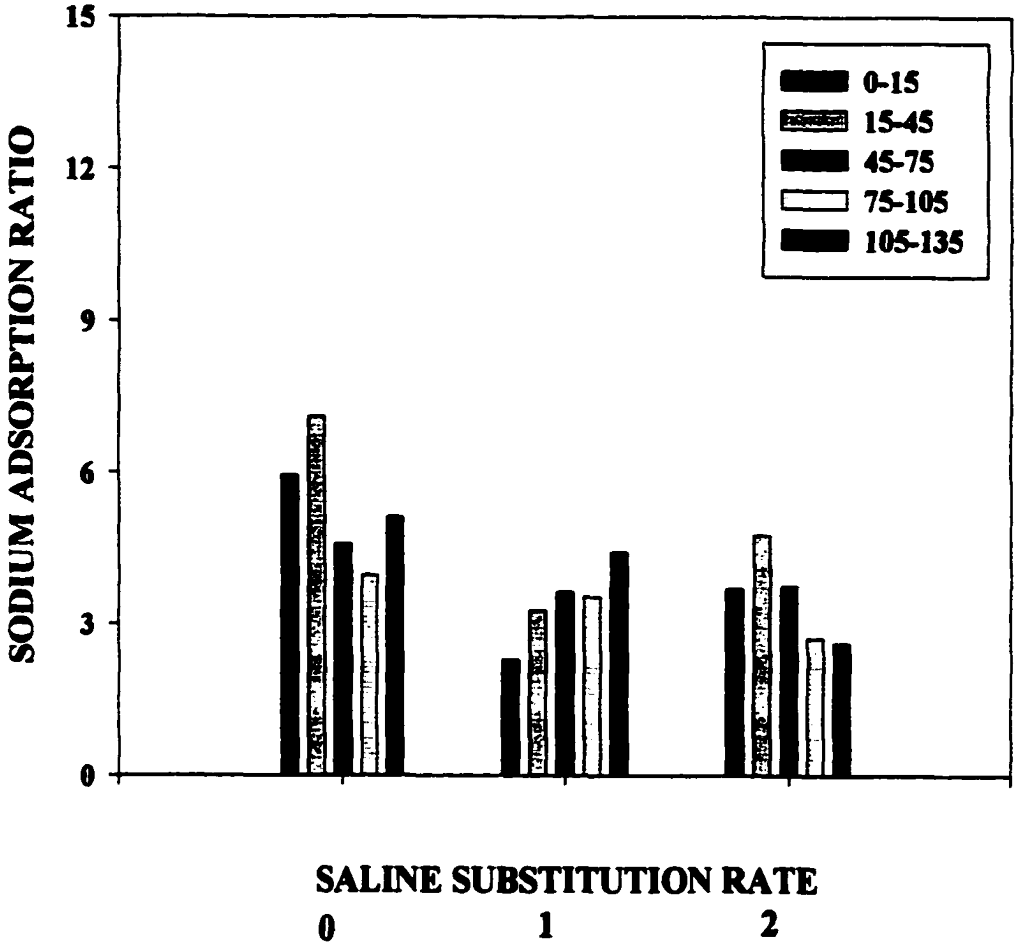

Fig. 32. Sodium adsorption ratios for all sample depths and treatments at the high school site for May 1998

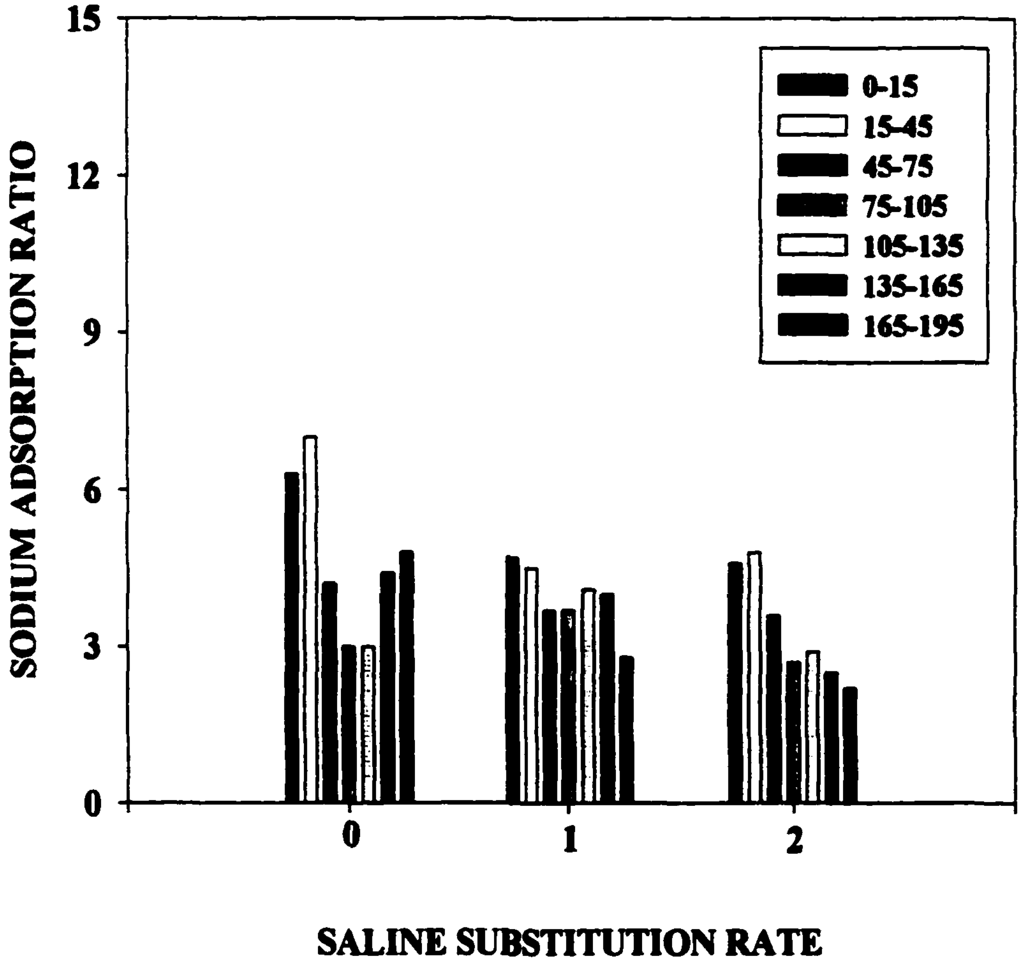

Fig. 33. Sodium adsorption ratios for all sample depths and treatments at the high school site for May 1999

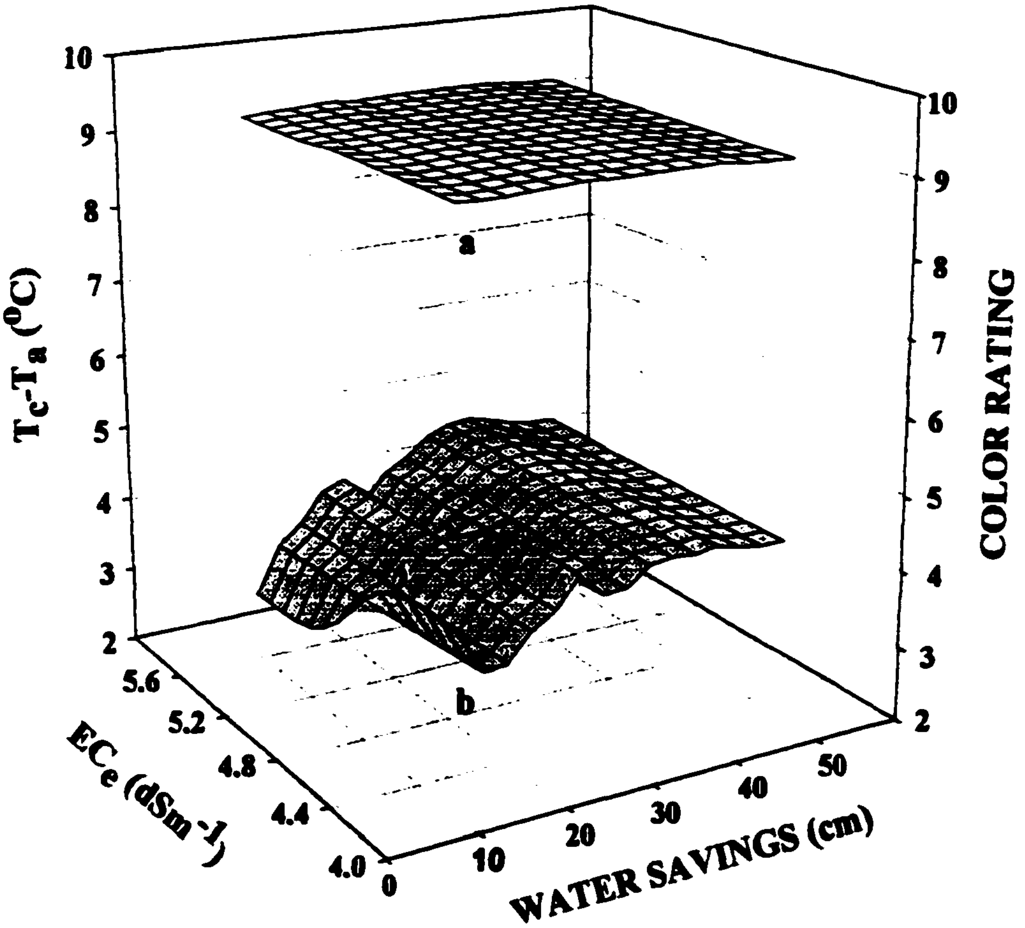

Fig. 34. Average water savings vs. depth weighted ECe 0-45 cm vs. color rating vs. canopy temperature (Tcanopy - Tambient) at the end of the two year experimental period, where (a) is color rating and (b) is canopy temperature for all substitution treatments at the University site.

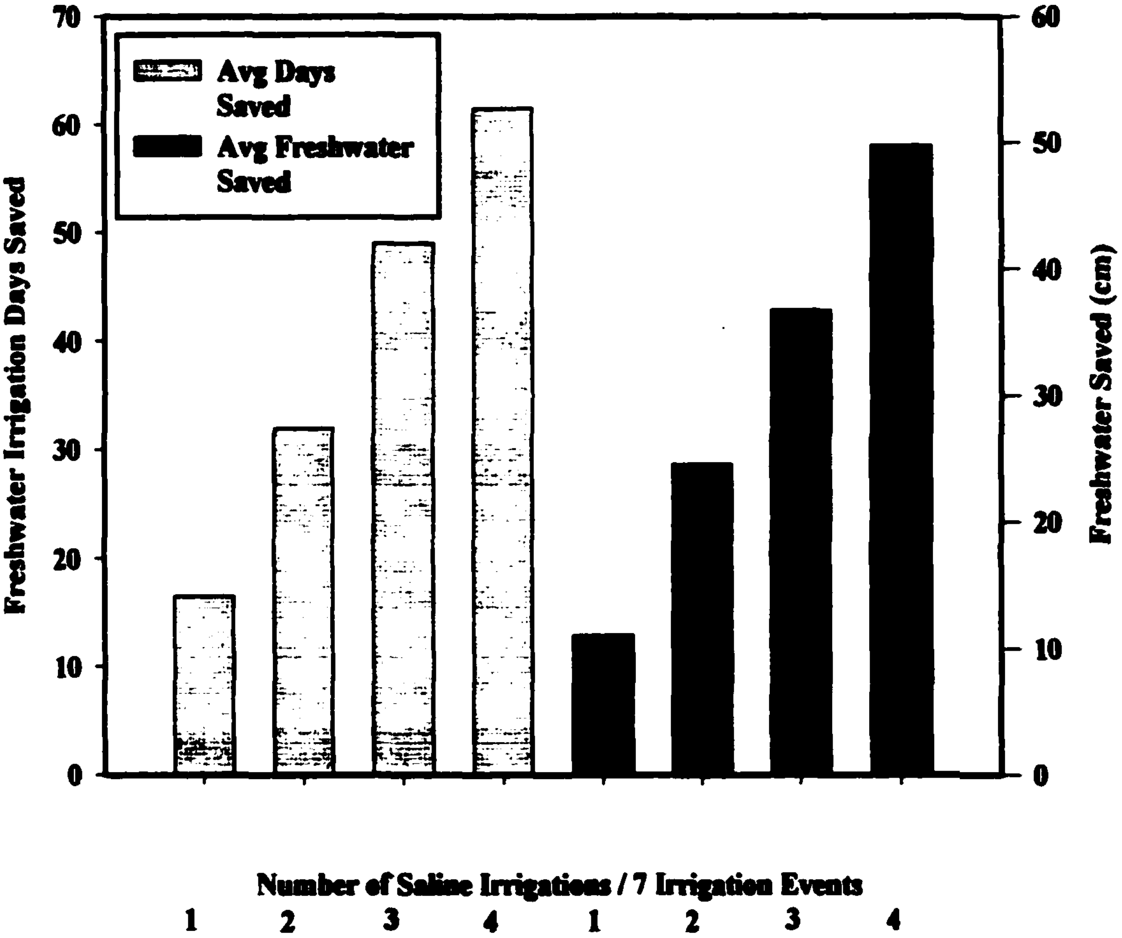

Fig. 35. Number of irrigation days and freshwater saved per saline treatment per peak demand period (May 15 - Oct 15) at the University site

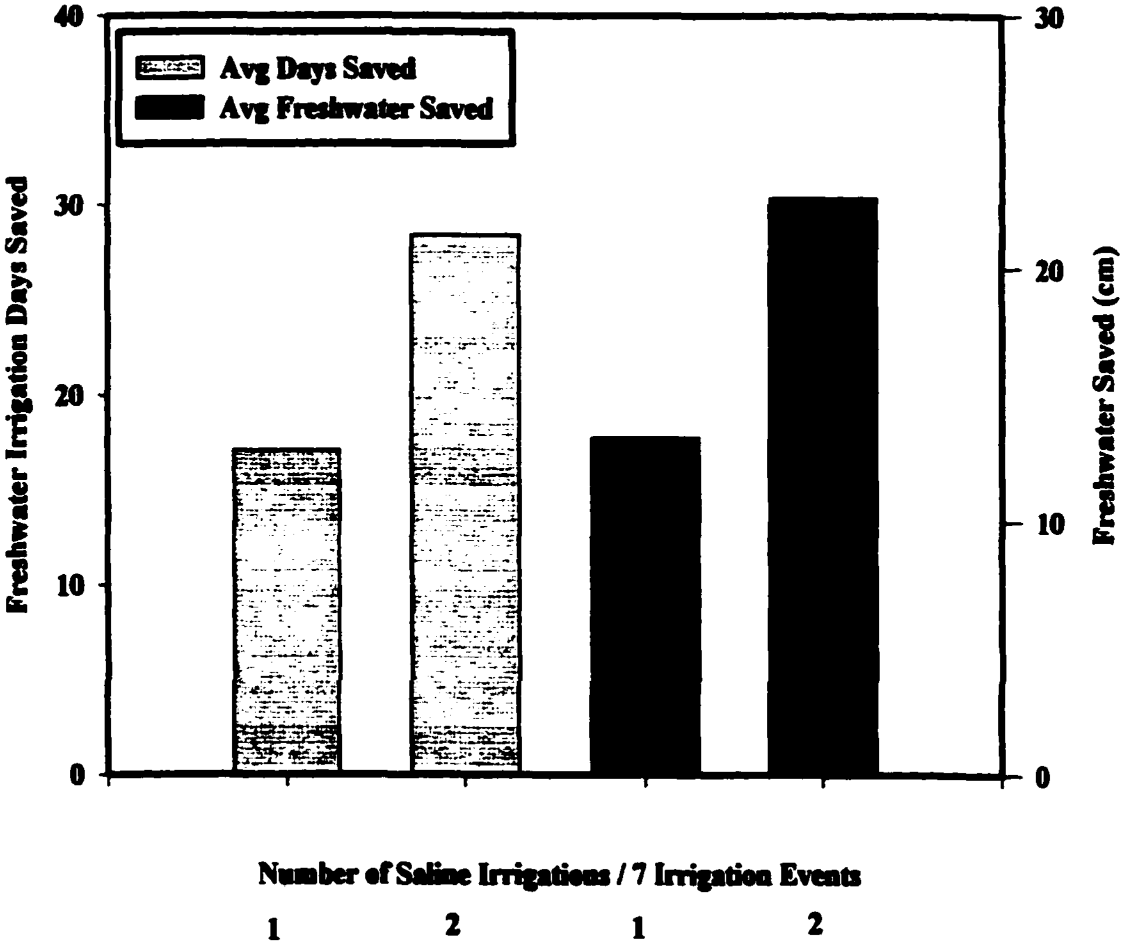

Fig. 36. Number of irrigation days and freshwater saved per saline treatment per peak demand period (May 15 - Oct 15) at the high school site

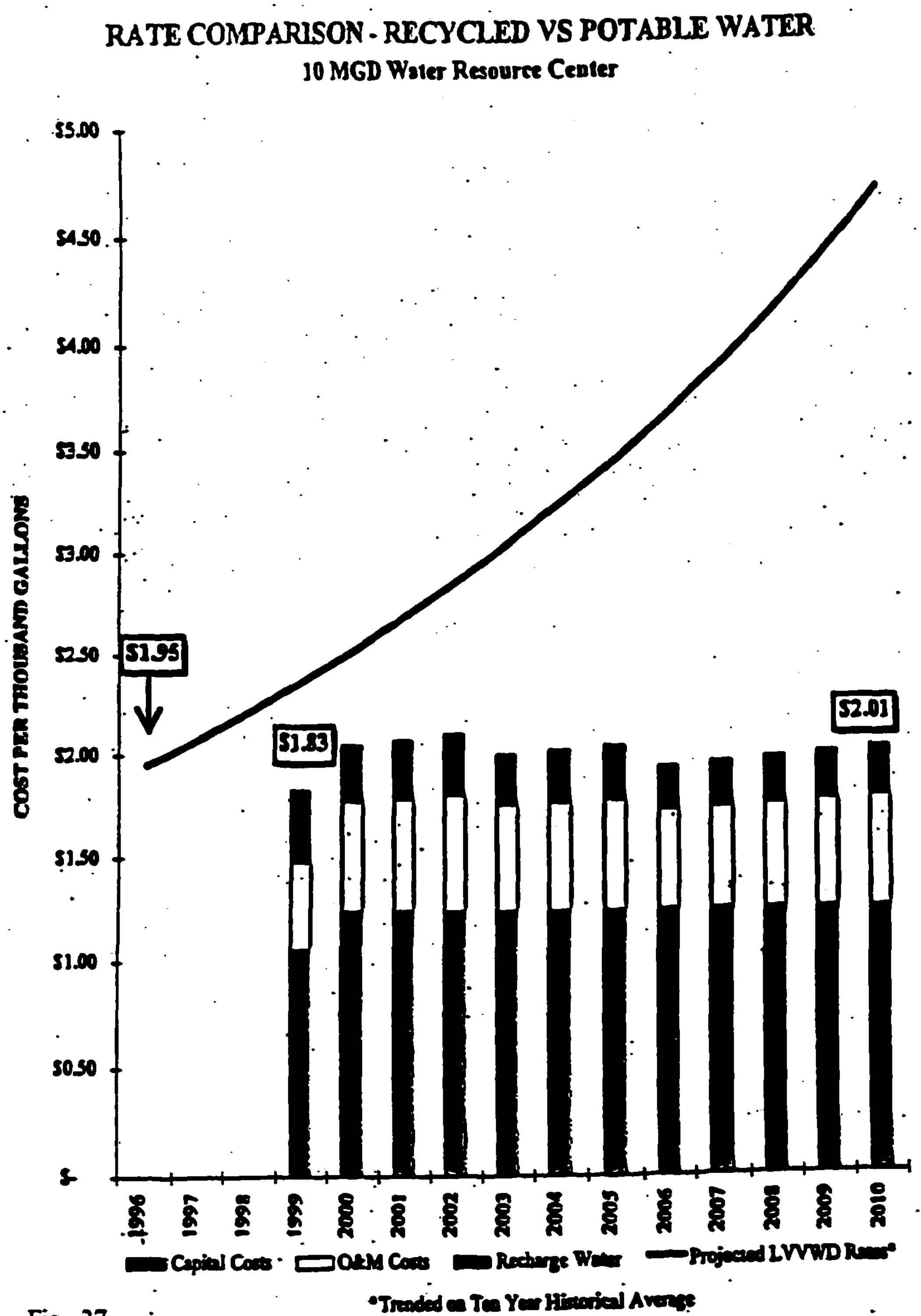
RATE COMPARISON - RECYCLED VS POTABLE WATER
10 MGD Water Resource Center
COST PER THOUSAND GALLONS
$5.00
$4.50
$4.00
$3.50
$3.00
$2.50
$2.00
$1.50
$1.00
$0.50
$-
$1.95
$1.83
$2.01
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Capital Costs
O&M Costs
Recharge Water
Projected LVVWD Rates*
*Trended on Ten Year Historical Average

Fig. 37.

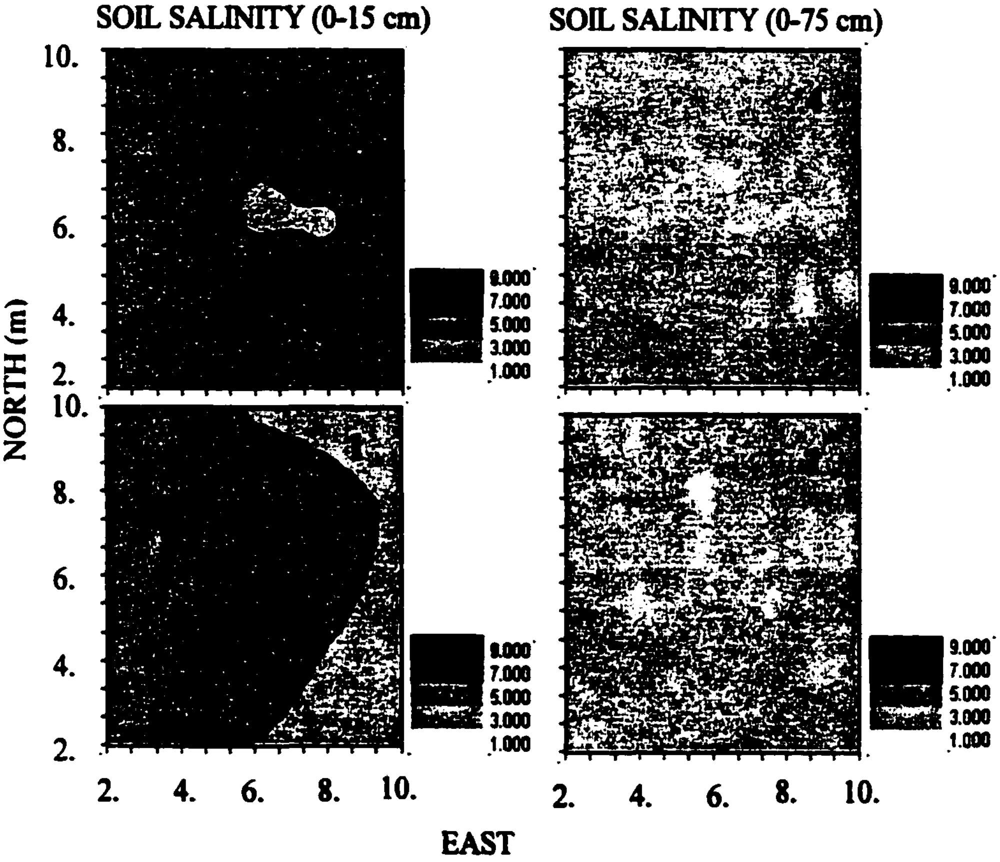

Fig. 38. Comparison of kriged isopleths for depth weighted soil salinity (0-15 and 0-75 cm, dSm^{-1}) for the 1 and 4 out of 7 saline substitution treatments at the University site at the end of the experimental period, May 1999

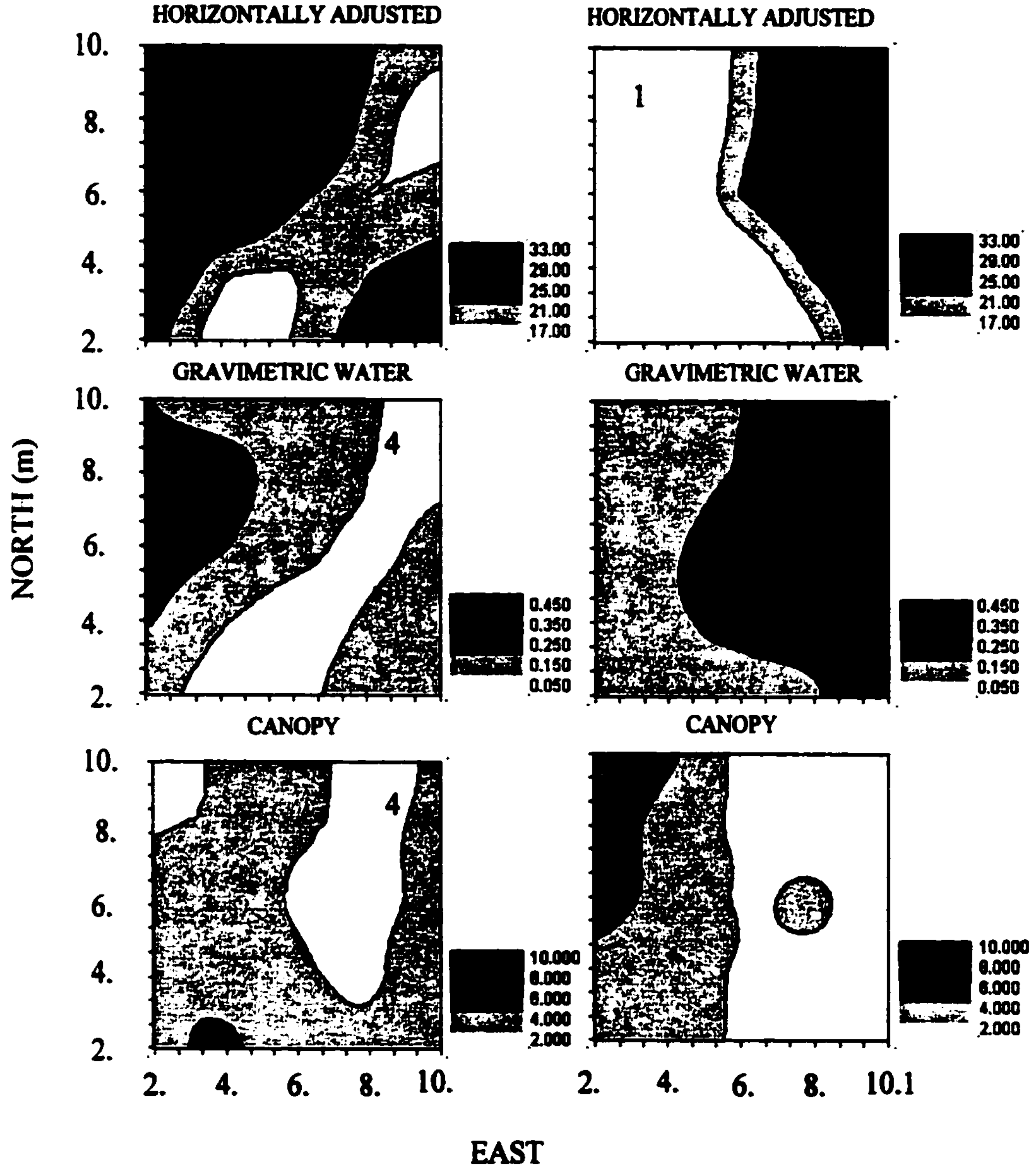

Fig. 39. Kriged isopleths of horizontally adjusted EM 38, gravimetric water content and canopy temperature for the 1 and 4 out of 7 saline substitution treatments at the University site at the end of the experimental period, May 1999

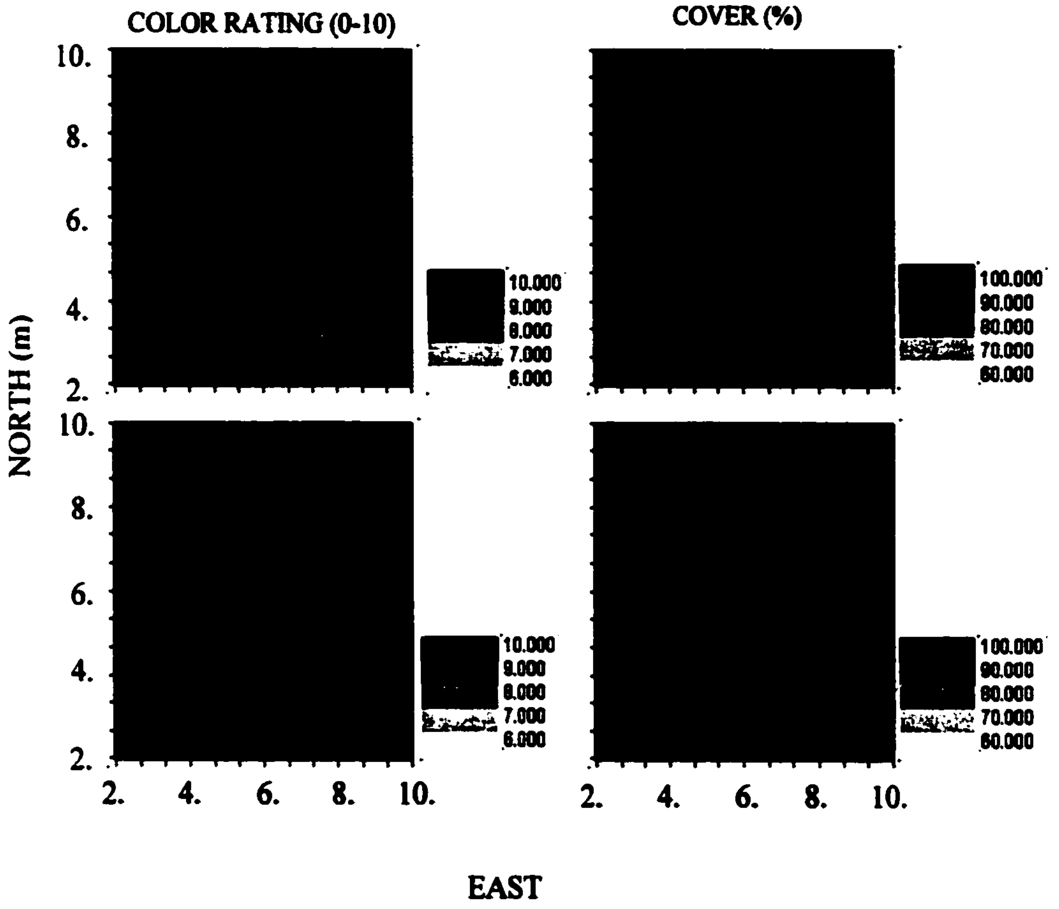

Fig. 40. Comparison of kriged isopleths of color rating and percent cover for the 1 and 4 out of 7 saline substitution treatments at the University site at the end of the experimental period, May 1999

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