TR-174

Gypsum and Polyacrylamide Soil Amendments Used With High Sodium Wastewater

Duane Gardiner

TEXAS WATER RESOURCES INSTITUTE

TEXAS A&M UNIVERSITY

FEBRUARY 1996

Gypsum and Polyacrylamide Soil Amendments Used With High Sodium Wastewater

Duane Gardiner
Texas A&M University-Kingsville
College of Agriculture and Home Economics
Campus Box 156
Kingsville, TX 78363

Project Number TXA&I-92-1
September 1, 1992 - August 31, 1994
Grant Number 14-08-001-G2048

The research on which this report is based was financed in part by the U.S. Department of the Interior, U.S. Geological Survey, through the Texas Water Resources Institute. Non-Federal matching funds were provided by the Texas A&M University-Kingsville. This report was adapted from a thesis by Bernardino Mendez-Gonzalez submitted in partial fulfillment of the M.S. degree.

Technical Report No. 174
Texas Water Resources Institute
The Texas A&M University System
College Station, TX 77843-2118

February 1996

ABSTRACT

Using wastewater for irrigation of crops represents an attractive alternative to disposal. Typically, municipal wastewaters are high in sodium, and the resulting high sodium absorption ratio (SAR) alters the soil structure making it more impermeable to air and water. The present study tested the hypothesis that gypsum applied after disking and anionic polyacrylamide (PAM) applied in solution reduce crust formation and improve the infiltration rate of water into soil irrigated with water high in salt and sodium. Two soil amendments were applied to plots furrow-irrigated with wastewater. The amendments were gypsum (11 Mg ha^{-1}), and PAM added to irrigation water at rates of 25 mg $L^{-1.}$ PAM applications were made during every irrigation and during every second irrigation. In addition, two column experiments were performed to measure hydraulic conductivity. In Experiment 1, PAM was applied to undisturbed soil profiles at rates of 5, 10, and 15 μg PAM cm^{-3} of soil. In Experiment 2, two levels of PAM (0 and 25 ml L^{-1}) and three levels of wastewater (20, 40, and 60 mm) were applied to disturbed soil profiles.

Field saturated infiltration (K_{fs}) rates of PAM-treated plots were approximately double those of the control, and significantly different ($P<0.05$) from non-irrigated plots. Gypsum was also beneficial but not as effective as PAM. The effectiveness of PAM persisted several weeks after the last PAM application. The results suggest that the deleterious effects of irrigation with this wastewater on soil permeability can be effectively ameliorated using anionic polyacrylamide

polymers. The ability of PAM to improve saturated hydraulic conductivity (K_s) in laboratory column studies was variable and not always correlated with levels of polymer added. Also, combinations of PAM and irrigation levels interacted significantly ($P<0.05$).

INTRODUCTION

The effective use and conservation of water in cities, industry and agriculture is taking on a new meaning as supplies become limiting. Contemporary water policies have the net effect of reducing availability of high-quality water for irrigation. However, as municipal and industrial uses of high-quality water increases, wastewater becomes available in increasing amounts.

Because wastewater is often discharged into surface waters for disposal (Berry et al., 1977) where components can contribute to eutrophication of lakes and streams, utilizing wastewater to irrigate agricultural crops represents an attractive alternative to disposal. Furthermore, many of the nutrients present in wastewater are already in a form usable to plants (Berry et al., 1977). Wastewater availability could allow maintenance of a productive irrigated agriculture, and in local areas could increase the value of land by allowing conversion of rainfed fields to irrigated fields. However, concerns for sustainability also dictate that users must identify the quality and quantity of wastewater to apply for maximum plant growth and minimal environmental pollution (Sanderson, 1986).

The goal of this study was to investigate crop management alternatives to minimize the hazards of sodium in wastewater used for irrigation. The specific objectives were to: i) evaluate the effects of treated wastewater on the permeability and surface crust formation of soils; ii) quantify the beneficial effects of additions of gypsum and PAM to ameliorate the deleterious effects of sodic wastewater on those soil physical properties.

LITERATURE REVIEW

The suitability of secondary-treated wastewater for irrigation can vary greatly depending upon the quality of the original water source, the intended use, and the specific treatment processes employed. Most wastewater is of urban origin. Major characteristics modified during treatment are biological composition, organic composition, and dissolved inorganic salts. To make the best use of wastewater, one must understand the characteristics that make it suitable for agriculture use as well as properties that could limit its use (Berry et al., 1980).

Reclaimed municipal wastewater is normally high in sodium and the resulting high sodium absorption ratio (SAR) is a major concern in planning wastewater reuse projects (Ayers and Westcot, 1986). Furthermore, the effects of sodium can be both direct (plant accumulation) and indirect (nutritional imbalance and impairment of soil physical conditions, such as crusting, water-logging, and poor permeability).

Suitability of wastewater for irrigation is evaluated on the bases of criteria indicative of its use (Ayers and Westcot, 1989). For potential hazards to soil physical properties evaluated in this study, the primary limitations of treated wastewater are the chemical constituents such as total dissolved salts, and the ratio and relative concentrations of sodium and calcium.

Total Dissolved Salts

Particle surface properties depend strongly on the types and amounts of adsorbed ions. In addition, high concentrations of specific ions deteriorate the physical properties of soil and limit plant growth. These ions are described as exchangeable because they can be replaced by other ions (Dexter and Chan, 1991). Thus, the soluble inorganic constituents of irrigation water react with soils as ions rather than as molecules (U.S. Salinity Laboratory Staff, 1954).

There are two standard methods for expressing soluble salt concentration: total dissolved solids (TDS), and electrical conductivity (EC). In addition, there is a linear relationship between the TDS and the EC of the water given as: TDS (mg L^{-1}) $\approx$ 640 X EC (dS m^{-1}) (U.S. Salinity Laboratory Staff, 1954).

Yield reduction occurs when salts accumulate in the root zone to such an extent that the crop is no longer able to extract sufficient water from the soil solution, resulting in water stress for a significant period of time (Ayers and Westcot, 1989). Leaching is the key to controlling salinity problems. The amount of leaching required depends upon the irrigation water quality and the salinity tolerance of the crop grown (Ayers and Westcot, 1989). Generally, salinity effects are more severe under hot, dry conditions than under cooler, humid conditions (Rhoades, 1972).

Sodium Content

The effects of sodium can be both direct (plant accumulation) and indirect (nutritional imbalance and impairment of soil physical conditions such as crusting, water-logging, and poor permeability). Exchangeable sodium enhances clay swelling and dispersion, which decreases soil permeability to water and air. Clay swelling and dispersion depend on the level of exchangeable sodium and salinity of the irrigation water and soil solution (Oster and Rhoades, 1986). The types and concentrations of exchangeable cations in soil are not constant, but vary in response to such factors as the quality of irrigation water (Dexter and Chan, 1991). When high sodium water is used for irrigation, difficulties may not appear during the irrigation season because high salinity may counter the effects of sodium. But when winter rains leach salts from the upper soil layer the sodium effect will be significant (Shainberg and Letey, 1983). Although, high salinity waters will increase infiltration, low salinity waters (rain) can result in poor soil permeability due to the tremendous capacity of pure water to dissolve and remove calcium and other soluble ions in the soil (Hillel, 1982). The exchangeable sodium percentage (ESP) of soils is correlated with decreases in permeability and toxicity effects on crops resulting from sodium (U.S. Salinity Laboratory Staff, 1954). An important consideration is the extent to which ESP of the soil will increase as a result of absorption of sodium from added water (Shainberg and Oster, 1978). The sodium absorption ratio (SAR) has been used advantageously in place of ESP for diagnosing sodicity.

The SAR of irrigation water (SAR_{iw}), in combination with the electrical conductivity of irrigation water (EC_{iw}), may be used to evaluate the sodicity hazard providing it can be related to the resultant SAR of the equilibrated soil water (SAR_{sw}). Seldom is the SAR_{sw} the same as that of the SAR_{iw}. For example, in waters having appreciable carbonates and bicarbonates, the CO_3 and HCO_3 precipitate in the soil as $CaCO_3$ thereby increasing the resultant SAR_{sw} (Rhoades et al., 1968).

A major factor affecting the final SAR_{sw} is the loss or gain of Ca and Mg due to precipitation or dissolution of alkaline earth carbonates. An additional factor is the introduction of Ca, Mg, and HCO_3 into the soil water system from weathering of certain soil minerals. Hence, mineral weathering complicates estimation of the fraction of Ca or HCO_3 in irrigation waters that precipitate in the soil (Rhoades, 1972). In general, precipitation tends to decrease Ca and HCO_3 concentrations in the soil solution, and mineral weathering tends to increase concentrations of these constituents. These two processes are difficult, if not impossible, to separate because the Ca and HCO_3 released to solution from weathering processes enter into cation-exchange and precipitation reactions (Rhoades, 1968). Ayers and Westcot (1989), introduced a practical approach to the SAR determination to account for the calcium solubility resulting from precipitation or dissolution during or following an irrigation. This approach considers the calcium concentration (Ca_x in meq L^{-1}) expected to remain in near-surface soil water following irrigation. The Ca_x is obtained using the HCO_3/Ca^{2+} (meq L^{-1}) ratio and the EC (dS m^{-1}) of the irrigation. Both the older SAR_{iw} procedure and the new R_{Na} are acceptable, with a preference for R_{Na} because it offers a better insight into the changes in Ca^{2+} in the soil water due to addition by dissolution of Ca^{2+} from soil carbonates and silicates, or loss of Ca^{2+} from soil water by precipitation as lime (Ayers and Westcot, 1989). Soils with high ESP have been shown to disperse when water of sufficiently low electrolyte concentration is introduced (Arora and Coleman, 1979). Dispersion and particle movement on the other hand are essentially irreversible, and cause the formation of impermeable clay pans (Shainberg and Letey, 1983). Soils with an ESP above 30 will usually have a poor physical structure and be poorly suited for crop production (Ayers and Westcot, 1989).

Because municipal wastewaters are normally high in salts, there is little concern for the water dissolving and leaching too much calcium from the surface soil. However, these waters are relatively high in sodium, and the resulting high SAR_{iw} is a major concern in planning wastewater reuse projects (Ayers and Westcot, 1986).

Wastewater Management Strategies

Gypsum Applications

Reclamation of sodic soils involves the replacement of exchangeable Na with Ca which can be supplied by the presence or addition of gypsum ($CaSO_4{\cdot}2H_2O$), soil lime ($CaCO_3$), or both (Oster and Frenkel, 1980). Gypsum is generally the amendment used because of its wide availability and low cost. The amount of gypsum required to reclaim a sodic soil depends on the amount of exchangeable Na in the soil profile (U.S. Salinity Laboratory Staff, 1954). Two main sources of gypsum can be used as soil amendment: mined and industrial, the latter being a by-product of the phosphate fertilizer industry. The efficiency of gypsum as an amendment depends on its dissolution properties (Keren and Shainberg, 1981). The actual processes involve simultaneous mineral dissolution, cation exchange, and solute and water movement (Oster and Frenkel, 1980).

Irrigation with water having a high Na:Ca ratio results in an increased Na saturation of the soil. To offset the deteriorating effects of this type of water, application of gypsum as a soil or water amendment is commonly recommended (Ayers and Westcot, 1989). Bajwa and Josan (1989) reported that applications of gypsum decrease pH, SAR (saturation extract) and ESP in the 0-60 cm soil layer as compared with treatments without gypsum. The changes are directly correlated with the level of applied gypsum.

Oster and Schroer (1979) found that the infiltration rate (IR) is very sensitive to the ESP and the salt concentration of the applied water. Ayers and Westcot (1989) stated that small repeated applications of gypsum to the soil may be effective in treating surface infiltration problems. Kazman et al. (1983) found that powdered phosphogypsum spread over the soil at the rate of 5 Mg ha^{-1} was very effective in maintaining a high IR in a sodic soil. Furthermore, they concluded that the final IR of a soil with an ESP of 11.6 was maintained at 9.6 mm h^{-1} when spread with phosphogypsum, compared with an IR of 0.6 mm h^{-1} in the untreated control. Also, Kazman et al. (1983) stated that in soil with moderately high ESP, a gradual increase in IR occurred as EC of the applied water was increased from 0.1 to 5.6 dS m^{-1}.

The ability of gypsum to maintain a moderate concentration of electrolytes in the percolating water is very important in preventing crust formation and soil sealing under rain conditions (Kazman et al., 1983). When the gypsum concentration in the soil solution is sufficiently high (> 5 mmol$_c$ L^{-1}) the tendency of the soil clay to disperse is low, and the IR is maintained at high values. Both the electrolyte concentrations and the replacement of exchangeable Na by Ca in the soil surface reduced the tendency of the soil to disperse and prevented it from forming a crust (Keren and Shainberg, 1981).

Polyacrylamide Applications

The dispersion behavior of soil due to high sodicity that result in poor aeration, poor water intake, poor drainability, and resist cultivation can be ameliorated by the addition or presence of gypsum into the water or soil, but initially, this is difficult to achieve (Oster and Frenkel, 1980). Also, gypsum applications may become inefficient in the presence of soluble Na salts. The common ion effect of $Na_2\ SO_4$ - ($CaSO_4{\cdot}2H_2O$) will drastically reduce gypsum dissolution, thus turning Na into the major cation regardless of gypsum applied (Nadler and Magaritz, 1986). Due to the processes involved it takes considerable time for the soil to attain good structure, and during this time economical returns may be low. It is evident that a quicker method of treating dispersed soils to restore good soil structure would be beneficial (Allison, 1952). Sherwood and Engibous (1953) noted that by proper use of synthetic soil conditioners a level of aggregation can be stabilized within hours or days. Incorporation of polymers in irrigation water may have potential benefits for maintaining or improving physical properties of the soil when irrigated with poor quality water.

The binding forces of clay depend on the exchangeable ions and charges present on the surface. These forces will increase as neighboring clay particles assume preferred orientations. Hence, any process conducive to proper orientation of clay particles increases clay aggregate stability (Harris et al., 1966). In general, soils of a high ESP and clay content which compact and crust badly or otherwise exhibit undesirable physical conditions have responded best to treatment with synthetic soil conditioners (Allison, 1952; Martin et al., 1952; Martin, 1953; Sherwood and Engibous, 1953).

Interparticle Bonding

Synthetic soil conditioners such as linear organic polymers possess functional groups and properties similar to soil and microbial polysaccharides. It is thought that the mechanisms involved in aggregation by synthetic polymers are similar to those involved in aggregation by some natural soil polymers (Harris et al., 1966). Martin et al. (1955) found that cohesiveness between clay particles depends on the binding force in aggregation rather than the cementing action of organic molecules. Harris et al. (1966) suggested that the cohesive force operating between clay particles may involve: i) linkage by a chain of water dipoles, ii) bridging between clay particles by polar long-chain organic molecules, and iii) cross-bridging and sharing of intercrystalline forces and interaction of exchangeable cations between oriented clay plates.

De Boodt (1972) stated that the ways soil conditioners change soil structure differ in categories from their chemical reactions with soil. The flocculating action of anionic water-soluble polymers is caused by adsorption of hydroxyl or amide groups on the particle surface, each polymer chain adsorbing on and bridging between more than one solid particle (Harris et al., 1966).

Factors Controlling Effectiveness

Stabilization effectiveness of natural and synthetic polymers is related to the configuration, molecular weight, degree of substitution, type of functional groups of the polymer, and any conditions of the soil system that influence polymer properties (Harris et al., 1966). There are at least three ways that polymers fix to clay: i) hydrogen bonding, ii) fixation of the anionic charges to clay minerals on the edge rather than on the negatively charged plates of clay minerals, and iii) sharing of polyvalent cations with the negative charges of clay and polyanions (Harris et al., 1966).

Effectiveness of conditioners as soil aggregate stabilizing agents are also influenced by soil texture or particle size and clay-mineral makeup (Martin, 1953). Thus, the amount of clay in the soil is an important factor in determining the aggregating efficiency of polyelectrolyte soil conditioners (Allison, 1952). For a given surface area of soil particles a specific quantity of conditioner is needed to produce maximum aggregation (Hagin and Bodman, 1954). Harris et al. (1966) found that further addition above the optimum level causes little additional increase in aggregation because all the active bonding sites of the soil are satisfied.

Allison (1952) stated that aggregation due to synthetic soil conditioners was as high on saline-alkali soil as on nonsaline-alkali soil, indicating that salinity did not inhibit the aggregation process. In addition, the presence of salts in solution with anionic polymers tend to help the fixation. When polysaccharides are present with anionic polymers in solution, fixation is easier and more complete (De Boodt, 1972). The nature of the clay, polymer and water quality have a considerable effect on the absorption of the synthetic soil conditioner into the soil. Aly and Letey (1988) and Ben-Hur et al. (1992) demonstrated that the absorption of the polymers was in the order cationic > nonionic > anionic in illite and montmorillonitic systems.

As a consequence of soil aggregation, changes in pore-size distribution, improvement in water infiltration, saturated water permeability, and soil tilth were obtained when using polyelectrolytic soil conditioners on alkali-soils. The changes are more pronounced in fine-textured soils than in coarse-textured soils (Martin et al., 1952). The resulting improvement in pore space can promote rapid leaching of salts, and, with simultaneous addition of a Ca salt, a decrease of sodicity can result (Wallace et al., 1986a).

Increased water infiltration from soil conditioner treatment is also reflected in decreased water runoff and soil erosion (Martin, 1953). In the Allison (1956) experiment using VAMA and HPAN soil conditioners, infiltration rate was increased from 0.51 inches per hour to an average of 3.10 inches per hour in a soil having an initial ESP of 29. Allison also demonstrated that the two soil conditioners reduced surface crusting at all levels of exchangeable sodium. However, in the absence of conditioner, soil crust formation was proportional to the ESP. Shainberg et al. (1990) found that a combination of PAM and phosphogypsum increased the infiltration rate 2 to 3 times over the control.

Because synthetic polyelectrolytes are organic, it is thought that they are subject to some degree of microbial attack which results in loss of effectiveness in maintaining a high degree of water-stable aggregation (Allison, 1952). Hagin and Bodman (1954) noted that after the polymer was fixed in the soil, it lost its ability to further influence aggregation after a mechanical mixing. Polyacrylamide may not be degraded biologically, but is degraded by cultivation, sunlight, and mechanical breakage. Wallace et al. (1986c) reported 10 % degradation of PAM per year in soils continuously cultivated.

Wallace, et al. (1986b) found a synergistic but indirect effect on crop response to N and P combined with PAM. The improvement of a limiting factor such as aeration, available water, or oxygen within the soil profile by the addition of PAM brings about the assimilation of fertilizers such as N and P.

Polyacrylamide conditioners have a potential benefit in maintaining or enhancing infiltration rates during succeeding water applications without conditioners (El-Morsy et al., 1991). Also, PAM polymers provide some stability to aggregates under high SAR and high electrolyte concentrations, but beneficial effects are reduced with time. The extent of clay flocculation of the optimal polymer treatment for soil aggregation is very complex and requires consideration of soil type, polymer type, concentration and water quality (Aly and Letey, 1988). A soil should be in good physical condition before PAM is applied because PAM does not improve soil with poor initial structure. Rather, it preserves the existing structure (Cook and Nelson, 1986).

At initial irrigation the introduction of PAM in the irrigation water at an effective concentration greatly increases viscosity of the water. This reduces the hydraulic conductivity because conductivity is inversely proportional to viscosity (Hillel, 1982). Within time, weakening of the soil strength with polymer applications renderers the furrow highly sensitive to weight of farm machinery, which pulverizes the treated clods on the surface (Mitchell, 1986). Hence, infiltration measurements after cultivation may show little effect of PAM in soil stability.

MATERIALS AND METHODS

The field experiment site was established at the Kingsville wastewater treatment plant, situated at 95° 50' W, 27° 31' N, about 800 meters east of U.S. Highway 77 on the south side of Farm to Market Road 2045 in Kleberg County, Texas. This area is part of the coastal plain of South Texas. The climate is subtropical and humid, with hot summers and mild winters.

The experiment was conducted on a Victoria clay soil (fine, motmorillonitic, hyperthermic udic pellusterts). The Kingsville wastewater treatment plant discharges an effluent volume of 4.5 million liters per day. Effluent characteristics are presented in Table 1.

Table 1. Components of municipal effluent water used in this study.

Species	Concentration		
	mg L^{-1}		
Na	410	EC dS m^{-1}	2.0
Ca	79	pH	7.7
Mg	28	SAR	10.1
CO_3	<1	R_{Na}	11.8
HCO_3	220	TDS mg L^{-1}	1420
Cl	480		
P	3		
K	18		
NO_3	21		
SO_4	350		
B	1		

This study consisted of three phases: Phase 1, December 1992 (field preparation) to June 1993 (last data collection) at the wastewater treatment plant site; Phase 2, July 1993 (field preparation) to May 1994 (last data collection); Phase 3, July 1994 involved two laboratory experiments.

Phase 1

The factors under study were i) gypsum applications at 0 and 11 Mg ha^{-1}; and ii) rates of wastewater application (control--the amount of water needed for germination, low--10 millimeters, and high--20 millimeters per irrigation). These six (2X3 factorial) treatments were arranged in a randomized strip-plot design with four replications for a total of 24 sub-plots. Each sub-plot was 5.5 m by 7.6 m. The gypsum used in this study was composed of 23% calcium and 16.5% sulfur (Agricultural Gypsum manufactured by Standard Gypsum Co, Fredericksburg, TX). Broccoli (*Brassica oleracea* var italica) was directly sown on 20 Dec. 1992 on rows 0.91 m apart with 0.30 m between plants. No fertilizer was used for this experiment. The irrigation treatments were applied from February to April, 1993, at levels of 100 mm and 500 mm. Two irrigations were applied in February and one each in March and April for four irrigations. Water was applied to furrows with a gated PVC pipe delivery system.

Commercial (fresh weight) and biomass yields (dry weight) of broccoli were collected from sections 3.05 m in length at the center of each plot. The criterion for commercial yield cutting point was 5 cm below inflorescence. For biomass yield, plants were cut at the soil surface.

The field saturated infiltration (K_{fs}) measurements were taken at the center-furrow of the high-irrigated and the non-irrigated treatments only, using the constant head well permeameter method (Elrick and Reynolds, 1992). The K_{fs} measurements (steady state flow) were collected the second week of May and the first week of June 1993.

These two data sets were analyzed using analysis of variance (ANOVA) for a randomized strip-plot design to determine treatment mean differences. Also, a Least Significant Differences (LSD) at $\alpha = 0.05$ test was performed to determine significant mean differences.

Phase 2

Five soil treatments were established. Treatment 1 had gypsum applied at the rate of 11.2 Mg ha^{-1}. Treatment 2 was PAM injected into the wastewater at the rate of 25 mg PAM L^{-1} per irrigation (12 liters of stock solution per 1351.8 liters of wastewater, where 1 liter of stock solution had a concentration of 3000 mg PAM L^{-1}). Treatment 3 was a lower PAM level in which PAM was injected as in Treatment 2, but only for every other irrigation. Treatment 4 was a control treatment, irrigated but with no soil amendment. Treatment 5 was 0 irrigation (just the amount of water needed for germination) and no amendments. Common bermudagrass (*Cynodon dactylon* (L.) Pers.) was sprigged-in on 12 August 1993 in rows 0.89 m apart and 0.3 m between sprigs. No yield data were collected from this crop. These five treatments were arranged in a randomized complete block design with four replications for a total of 20 plots. Each plot was 2.7 m by 7.6 m (3 adjacent furrows per plot). Gypsum (same as in Phase 1) was applied followed by disking twice to incorporate the gypsum to a 5-10 cm depth. Information on irrigation rates and treatment schedules are presented in Table 2. Water was applied to furrows with a gated PVC pipe delivery system until the water advanced to the end of the field (22.8 m long). Irrigation continued for 10 minutes. Tailwater was allowed to flow beyond test plots. The anionic polyacrylamide was injected with an electronic metering pump (PULSATRON®, manufactured by PULSAFEEDER® Punta Gorda, FL) at 90 % stroke and 100 % stroke length to dispense the correct amount. No fertilizer was used in this experiment.

Soil samples from 30 cm deep and from 3 locations along the center furrow of the plot were collected and thoroughly mixed to form a composite sample. The composite sample was then used to determine the particle size distribution by the hydrometer method (Sheldrick and Wang, 1993). Also, the composite sample was used to determine the water (moisture) content by the microwave oven method (American Society for Testing and Materials, 1992). A second set of soil samples from one location (middle of furrow) and along the same furrow as before, under five depths (152, 305, 457, 610, and 914 mm) was collected to determine pH (Hendershot et al., 1993). Electrical conductivity measurements were made on saturation paste extracts (Janzen, 1993). In addition, sub-samples from 152 and

305 mm depths were sent to A&L Plains Agricultural Laboratory (Lubbock, TX), to be analyzed for chemical characteristics.

Soil surface penetrometer resistance (soil crust) was measured using the Lang Penetrometer (Lang Penetrometer, Gulf Shores, AL). Seven measurements were taken along the center furrows of each plot (3 adjacent furrows per plot) starting from top of the furrow (erosional zone) to the bottom of the furrow (depositional zone). These measurements were taken on 25 February 1994. The means of these seven measurements were compared to test for treatment differences.

The field saturated infiltration (K_{fs}) rates of wastewater were measured using the constant head pressure (single-ring) infiltrometer method, sometimes referred to as the "Guelph pressure infiltrometer" method (Elrick and Reynolds, 1992). The K_{fs} measurements were taken at two locations: top of the furrow (erosional zone) and bottom of the furrow (depositional zone), using a hydraulic head of 12.5 cm. Three readings were taken at each location to obtain a mean. The schedule of data collection for the two locations was as follows. In the depositional zone the first readings were taken from 24 to 27 January; the second readings were taken from 31 January to 6 February; and the third readings were taken on 11 February. In the erosional zone the first readings were taken on 18 February; the second reading were taken from 24 to 25 February; and the third readings were taken on 4 March.

These three sets of data were analyzed using ANOVA for a randomized complete block design to test treatment mean differences and an LSD test at $\alpha = 0.05$ to determine significant mean differences.

Total weekly and monthly rainfall corresponding to the duration of Phase 1 and Phase 2 (field studies) was recorded from a rain gauge located 2 km from the experiment site (Patrick Conner, Kika de la Garza Plant Material Center Kingsville, Texas; and The National Oceanic and Atmospheric Administration, Kingsville, Texas, weather station).

Table 2. Irrigation and treatment schedule,† 1993.

Date	PAM Applications		Irrigation
	High-PAM	Low-PAM	(cm)
August			
9	Yes	Yes	2.2
12-14	No	No	4.4
16-17	No	No	4.4
20	Yes	No	2.2
September			
6	Yes	Yes	2.2
21	Yes	No	2.2
October			
8	Yes	Yes	2.2
November			
21	Yes	No	2.2

†PAM applications at 25 mg L^{-1} wastewater. The period 12 to 17 August represents plant establishment.

Phase 3

Experiment 1

This experiment was done to quantify effects of rates of PAM application on hydraulic conductivity. Trenches of about 3.5 m long and 0.3 m in depth were made at the field experiment site, in soil free of previous soil treatment effects. Twenty PVC cylinders, 10.2 cm in diameter (inner) and 17.1 cm in length, were used as columns. These columns were placed on top of the trenches and driven into the soil with a hammer. After collecting the soil profiles from the field, a desired depth of soil within columns was obtained ($\approx$10 cm) by removing the excess soil from the bottom of the profile. To keep the soil in place, a double layer of cheese cloth was placed in the bottoms of the columns and fastened with tape. The final soil volume per column was 817 cm^3.

Four rates of anionic polyacrylamide (PAM) were applied to these columns. Rates applied were 0, 5, 10 and 15 μg PAM cm^{-3} of soil. Treated columns were arranged in a completely randomized design with five replicates, for a total of 20 columns.

The experiment was performed in the laboratory measuring saturated hydraulic conductivity (K_s) by the constant head method (Klute and Dirksen, 1986). After presoaking (wetting from below by capillary rise) each column for 2-4 hours, the K_s was measured three times per column. The mean of each column was statistically analyzed using ANOVA to detect any treatment mean differences. Also, LSD at $\alpha = 0.05$ was used to detect significant mean differences.

Experiment 2

This experiment was done to test for interactions between irrigation levels and PAM rates. Thirty-six columns having the same dimensions as in Experiment 1 were used. Soil free of previous treatment effects was collected from the upper 15 cm of the experiment site and passed through a 10-mm sieve. The sieved soil was collected and placed in the columns to simulate tillage. The amount of soil used per column was about 819 g oven dry ($\approx$10.6 cm depth).

Treatments of two levels of PAM (25 mg L^{-1} and 0) and three levels of wastewater addition (20, 40, and 60 mm) with six replicates were arranged in a completely randomized factorial design with 36 columns. Measurements were made using the same methodology as described for Experiment 1.

The ANOVA for a completely randomized factorial design was used to determine any treatment differences and LSD at $\propto = 0.05$ was used to determine significant mean differences.

RESULTS AND DISCUSSION

Phase 1

Crust formation estimates were not performed during this phase, because climatic conditions (rainfall and cool temperatures) of the region at this time were not suitable to induce crust formation. However, previous studies by Gardiner et al. (1991) at the same location revealed that significant soil crusting occurred in furrows receiving 394 mm and 629 mm irrigation rates over a 5-month period. Gypsum did not significantly reduce crust formation.

Statistical analyses performed on the average infiltration rates over each of these irrigation levels and soil treatments showed no significant ($P>0.05$) treatment differences existed, nor did a significant interaction exist between irrigation levels and soil treatments. These results were inconsistent with studies regarding the ability of gypsum to prevent crust formation and to increase infiltration rates (Keren and Shainberg, 1981; Shainberg et al., 1982; Kazman et al., 1983; Ayers and Westcot, 1989). A dominant factor controlling the effectiveness of gypsum to reduce clay dispersion, reduce crust formation, and increase infiltration is the potential of the soil to release divalent cations from the soil surface (exchange sites) due to dissolution by rainfall and soil mineralogy. Thus, when water of salinity below 1 mg L^{-1} (rain or snow water) is applied to soils, even Ca-rich soil and soil of low ESP may disperse and lose some permeability (Shainberg and Letey, 1983; Kazman et al., 1983). Ben-Hur et al. (1992) noted that powdered gypsum did not affect the infiltration amounts where the soil surface was undisturbed, and that the effect of surface-applied gypsum to increase infiltration would be short-lived. This may partially explain the inconsistent results found in this phase. During this experiment a considerable amount of rainfall was received (about 840 mm). In addition, the gypsum was applied at the soil surface months before irrigation began.

Broccoli yields for the 0 and 10 mm irrigation level were significantly different for both fresh and dry weights. No significant ($P>0.05$) differences were found between the 0 mm and the 20 mm levels, nor between the 10 mm and 20 mm levels (Table 3). Mean fresh and dry yields of broccoli as a function of irrigation amounts are plotted in Figure 1.

No significant ($P>0.05$) differences in fresh weights or biomass of broccoli were obtained from gypsum treatments. Similar results were found by Gardiner et al. (1991) growing bell pepper at the same location.

Table 3. Mean commercial fresh weight and biomass dry weight of broccoli grown under 3 irrigation levels at the wastewater treatment plant.

Irrigation Level	Commercial fresh weight	Biomass dry weight
mm	---------------- kg m^{-1}	------------------
0	0.85 b[†]	0.19 b
10	1.28 a	0.30 a
20	1.13 ab	0.29 ab

[†] Within a column, means not followed by the same letter are significantly different by LSD ($P<0.05$).

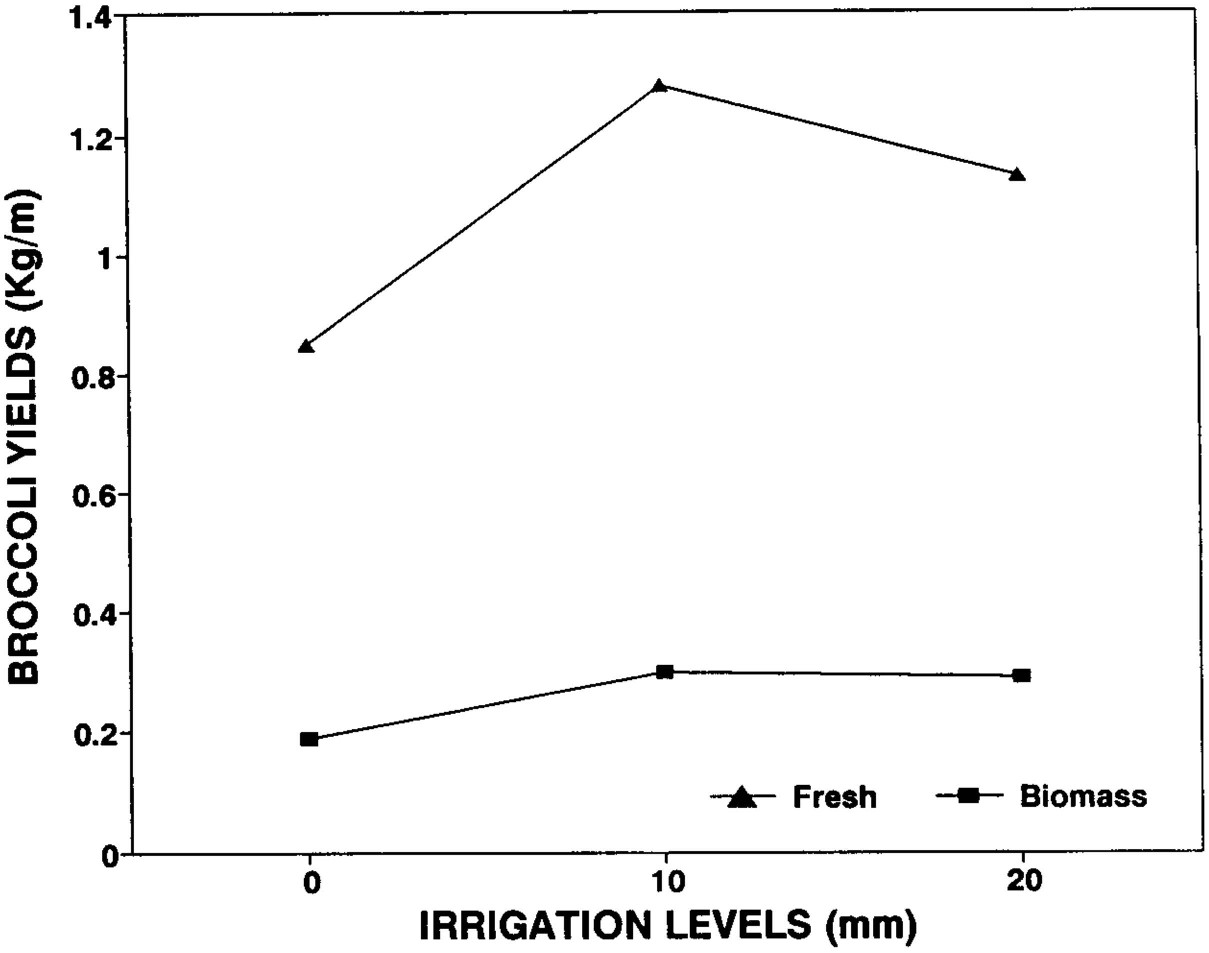

Fig. 1. Mean commercial fresh weight (inflorescence) and biomass dry weight of broccoli in reponse to irrigation levels.

Phase 2

Texture

The soil particle size distribution (texture) in each of the five soil treatments at the two positions (furrow head and furrow tail) within a depth of 30 cm were clay loam with a mean clay, silt, and sand content of 39, 20 and 40 % on a dry mass basis. Texture differences among treatments and within positions were not significant ($P>0.05$).

Moisture

The water content in response to treatment and position is plotted in Figure 2. Soil water content was significantly ($P<0.05$) affected by the interaction between treatment and furrow position. The soil moisture content of the High-PAM treatment was higher at the tail than it was at the furrow head; the inverse is more common. It has been reported that the addition of synthetic soil amendments does not increase the amount of available moisture in the treated portion of the soil (Sherwood and Engibous, 1953). Therefore, the amount of moisture present in the treated soil may have been increased by the increase in infiltration (Figure 7), and to some degree to the reduced evaporation caused by a mulching effect of the surface-stabilized soil aggregates.

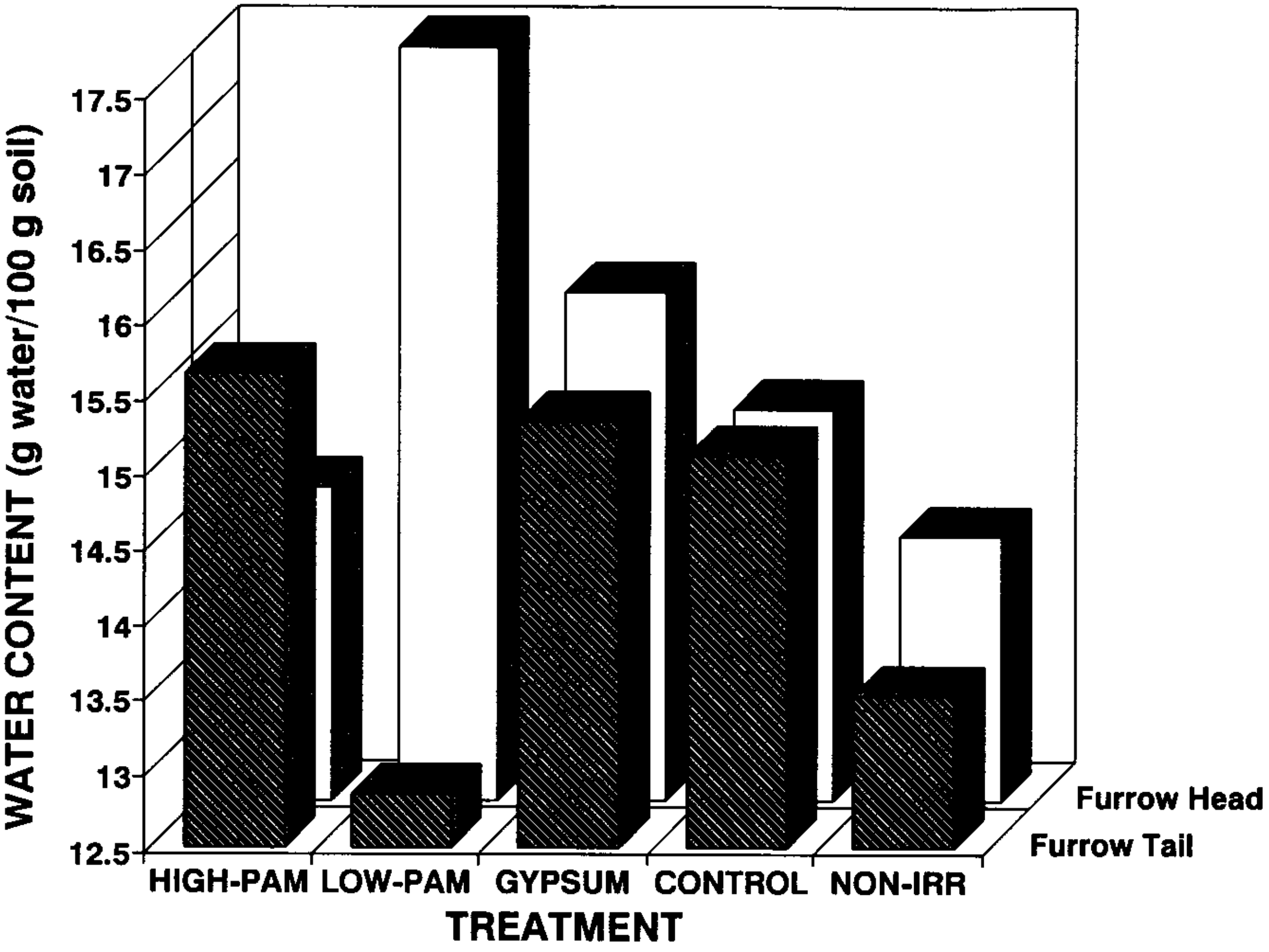

Fig. 2. Soil moisture content (g water 100 g^{-1} soil) in response to treatment and furrow position.

Soil pH and Electrical Conductivity

Statistical analysis of pH and EC indicate treatment differences were not significant ($P>0.5$). Significant differences in pH ($P=0.0036$) and EC ($P=0.0001$) were found among depths (Table 4). Soil salinity increased with depth from 0.5 dS m^{-1} at the 152 mm depth to 2.4 dS m^{-1} at the 914 mm depth, (Figure 3).

In general, changes in soil (mineral) pH affect the charge on clay. At low pH, edge to face clay (mineral) bonding is expected which will hinder dispersion and result in optimum hydraulic conductivity. At high pH, edge to face clay (mineral) bonding decreases because iron and aluminum bonding to clay decreases (Suarez et al., 1984). Thus, soil with high pH create a weaker bond at the soil surface where dispersion may occur as a result of the impact of rain or sprinkle irrigation, unless anionic charges are attached to the aluminum-clay bond. Adverse effects of exchangeable Na on soil hydraulic conductivity are magnified by high soil and water pH in semiarid and arid regions (Suarez et al., 1984).

When the soil is leached with low salinity water (rain water) even ESPs of 5 may be detrimental (Oster and Schroer, 1979). It is important to note the low electrical conductivity at the soil- surface (EC_{ss}) 305 mm layer (Figure 3), because the water used for irrigation had an EC =2.0 dS m^{-1} (Table 1). Perhaps the low EC_{ss} was due to the distribution of rainfall (Figure 4) received during this phase. This factor and the high sodium water used for irrigation (Table 1) could increase the chances of low permeability. Shainberg et al. (1980) stated that the marked effect of low electrolyte levels on soil permeability is especially pertinent to the surface layer of the soil because of the mechanical action of the applied water and the absence of a soil matrix.

Table 4. Mean soil pH and electrical conductivity (EC) at 5 depths (n=100).

Depth	pH	EC
mm		dS m^{-1}
152	8.4 a[†]	0.67 a[†]
305	8.3 b	0.94 b
457	8.2 c	1.26 c
610	8.2 c	1.56 d
914	8.1 d	1.73 e

†Means in a column followed by the same letter are not significantly (P>0.05) different using LSD.

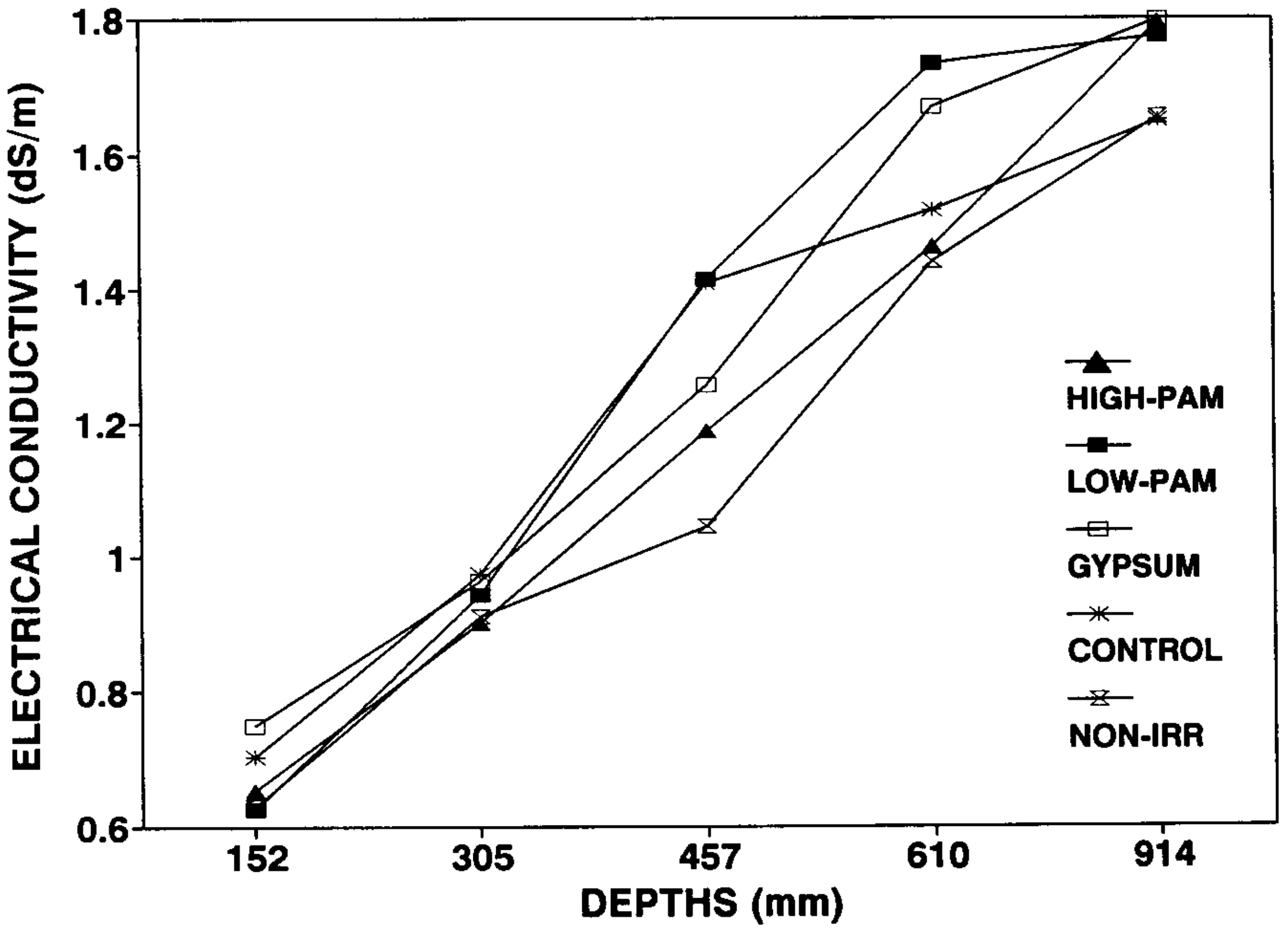

Fig. 3. Soil electrical conductivity means from 4 blocks as a function of depth in response to soil treatment.

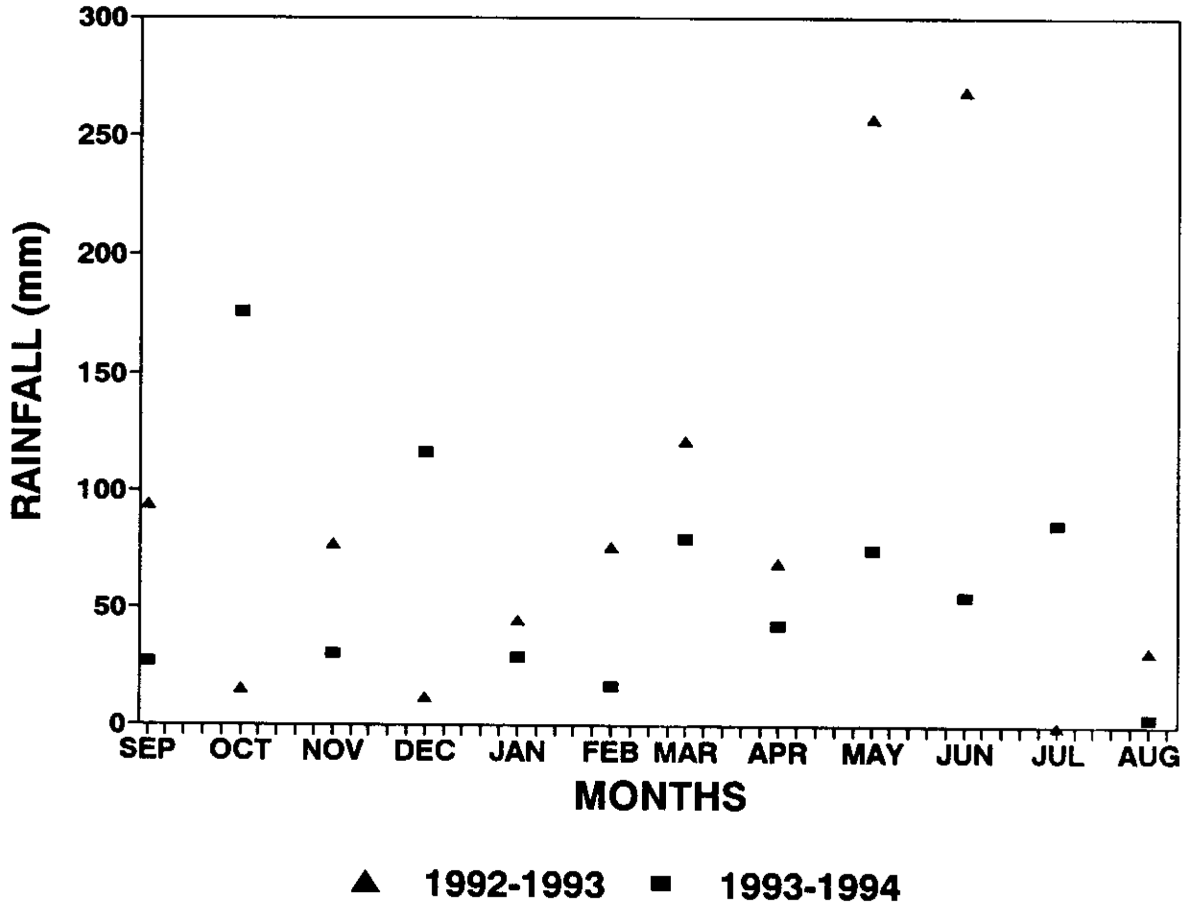

Fig. 4. Total monthly rainfall for the field experiment period at the wastewater treatment plant.

Soil Chemical Characteristics

Calcium was the most common cation at both the 150 mm and 305 mm depths (Table 5). None of the soil chemical characteristics were significantly different among treatments or depths.

The wastewater used for irrigation provided medium to very high nutrient concentrations. Even though crop productivity was not measured, the physical appearance of the crop was healthy and highly productive (judged by visual criteria).

The differences among soils in their capacity to release salt and to affect these mentioned soil properties appears to be especially important under heavy rainfall conditions. Exchangeable sodium percentage (ESP) did not affect the permeability of the soil even when the soluble salts were less than 1 dS m^{-1} at the soil surface. Oster and Rhoades, (1986) stated that if the R_{Na} in the top soil is greater than 10, then a large reduction in permeability can occur if rainfall reduces soil salinity to levels less than 1 dS m^{-1}. Rhoades et al. (1968) stated that the impact of the R_{Na} can be reduced by the *in situ* soil-mineral weathering which is of sufficient magnitude to alter the evaluation of the Na hazard of some waters to the soil. Perhaps this partially explains the high content of calcium found in the experimental site and the leaching of salts, nutrients, and/or water to lower soil layers.

Table 5. Soil chemical characteristics at two depths.

Soil Depth	Ca	K	Na	Mg	P	Soluble Salts	CEC	ESP	pH	OM
mm	------------------ mg kg^{-1} † ---------------					dS m^{-1}	cmol$_c$ kg^{-1}	%		g kg^{-1}
150	3107	548	493	365	41	0.62	22	10	8	13
305	3478	487	528	378	26	0.66	23	10	8	13

†Readily available.

Crust Formation

Results from penetrometer resistance measurements showed that treatments did not affect crust formation. Values ranged from 2.13 MPa for the irrigated control to 1.6 MPa for the non-irrigated treatment. Crop conditions at sampling time might be the most important factor to consider here. The crop (bermudagrass) was fully developed at the ridge area, and runners were spreading to the furrow area where irrigation was applied. Consequently, crust formation may have been impaired by the dense bermudagrass. Ben-Hur et al. (1989) also found that crust can be prevented by a dense crop canopy.

Infiltration

The effects of PAM amendment on maintaining soil structure were visually apparent in the field. Less erosion and improved structural stability were obvious in PAM-treated plots. The High-PAM average saturated infiltration rate (K_{fs}) was approximately double the control, and significantly ($P<0.05$) different from those of the control and non-irrigated treatments, at both the head and tail of the furrows (Table 6). In addition, low-PAM and gypsum treatments resulted in K_{fs} values higher than the control. Saturated infiltration rates 63 days after final flood-irrigation with and without PAM and gypsum treatments are plotted in Figures 5 and 6 by furrow position.

Table 6. Mean saturated infiltration rates at the soil-surface taken from the furrow head and furrow tail under five treatments.

Treatment	Infiltration Rates	
	Top	Bottom
	------------------------- mm min^{-1}	-------------------------
High-PAM	5.22 a†	4.87 a†
Low-PAM	4.61 ab	4.11 ab
Gypsum	4.18 abc	4.02 ab
Control	2.64 c	2.58 c
Non-irrigated	3.58 bc	3.26 bc

†Within a column, means not followed by the same letter are significantly different by LSD ($P<0.05$).

This implies that PAM applications into high sodium irrigation water preserved the initial porosity of the soil-surface through several rainfall events. In addition, porosity facilitated the entry of water, as opposed to control treatments where passage of water may have been hindered by the swelling and shrinking of the soil. The significant difference in infiltration readings taken more than 60 days after the last PAM application suggests that lower or less frequent applications of PAM may be optimal. Ben-Hur et al. (1989) stated that the effectiveness of polymers to maintain high infiltration rates in consecutive water applications is important from a practical point of view, because it determines whether the polymer needs to be supplied repeatedly or only in the first water application.

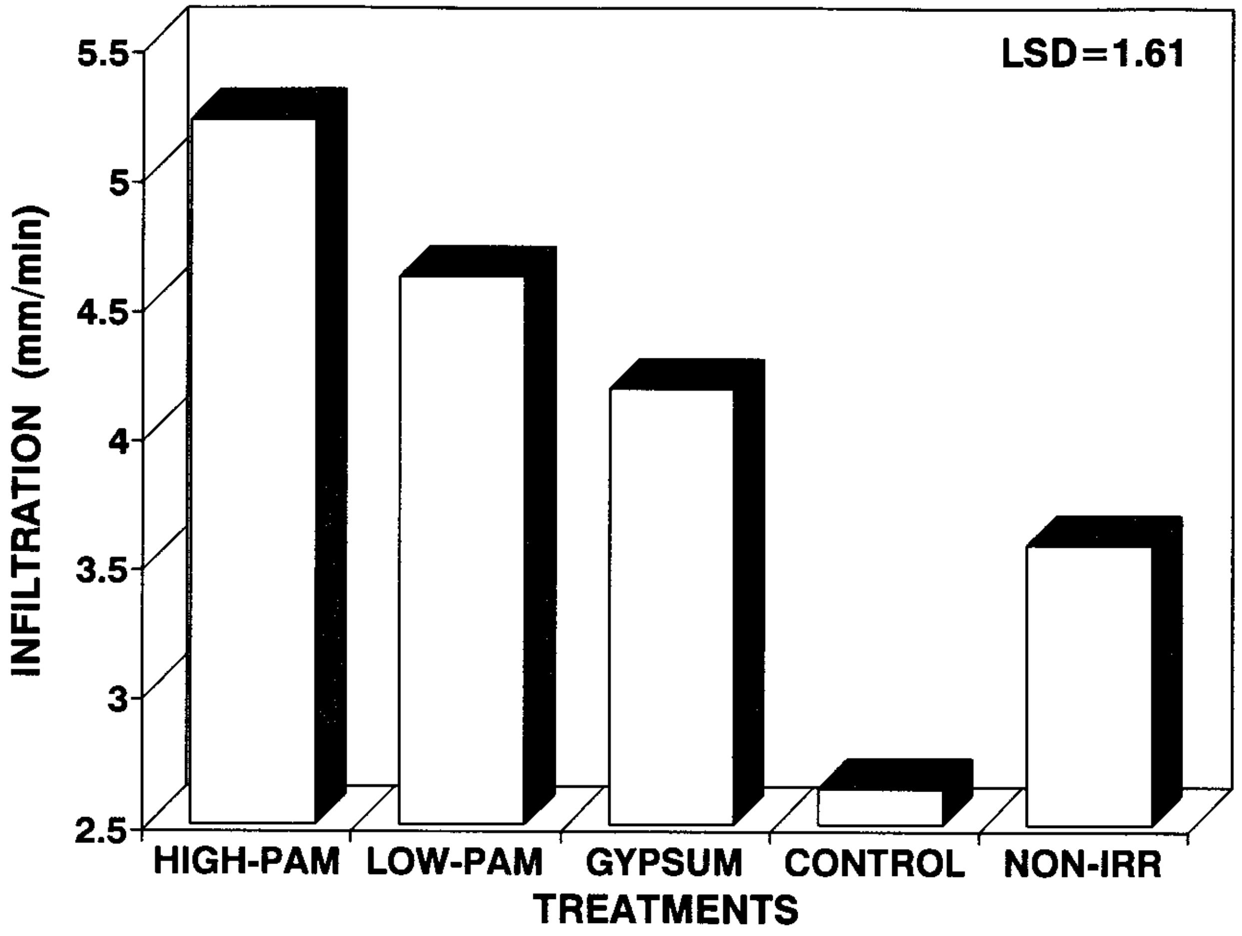

Fig. 5. Mean infiltration measurements at the soil surface taken at the head of the furrows (erosional zone) as influenced by soil treatments.

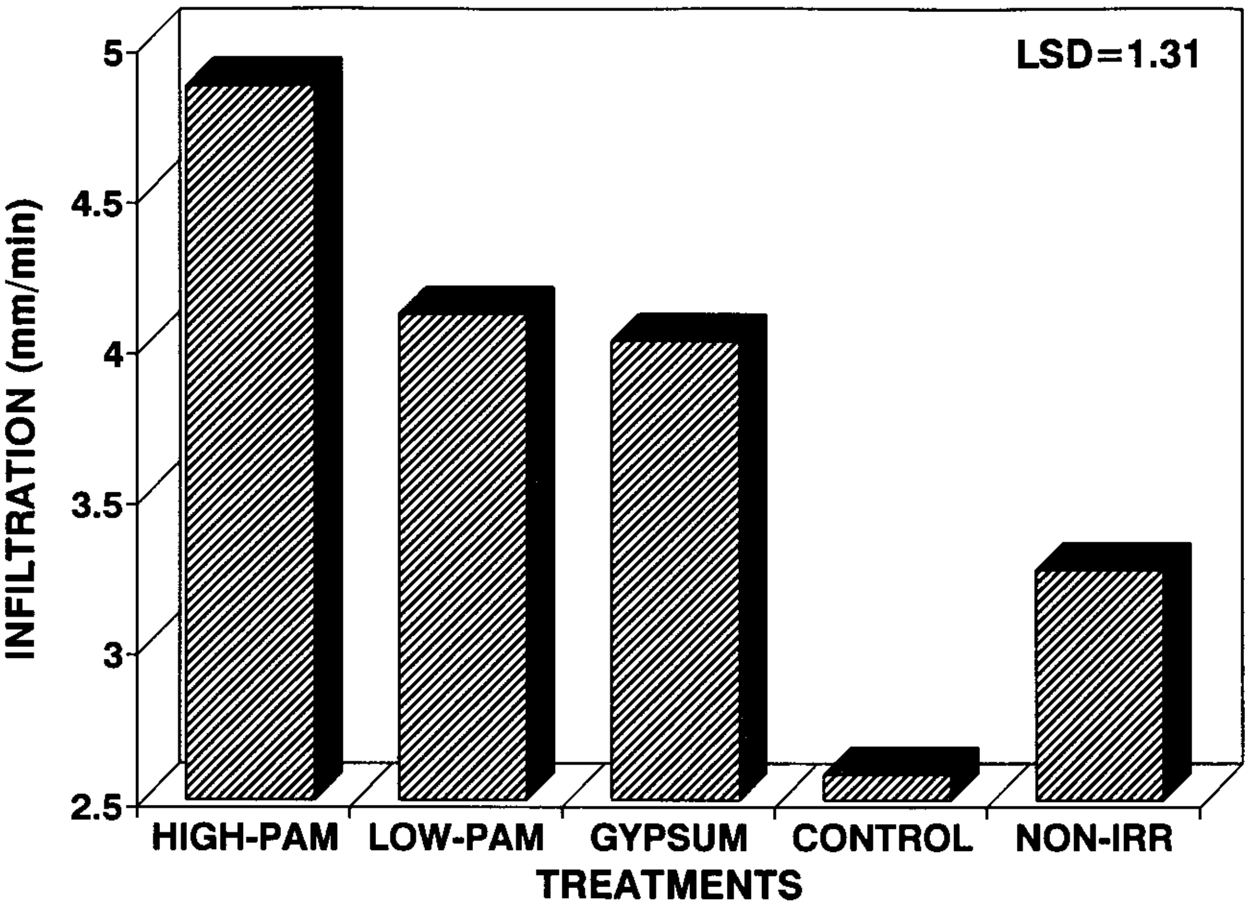

Fig. 6. Mean infiltration measurements at the soil surface taken at the tail of the furrows (depositional zone) as influenced by soil treaments.

Phase 3

Experiment 1

Undisturbed soil profile column saturated hydraulic conductivity (K_s in mm sec^{-1}) data was collected. Mean K_s values were not significantly ($P>0.05$) different for PAM levels between 0 and 5, or 10 and 15 μg PAM cm^{-3} soil. Significant ($P<0.05$) differences were found among PAM levels of 0-5 and 10-15 μg PAM cm^{-3} soil (Table 7). The ability of PAM to improve K_s was variable and not always correlated with levels of PAM added (Figure 7). Concentrations above an optimum cause little or no increase in aggregation because all the active bonding sites of the soil are satisfied (Harris et al., 1966). A possible factor affecting K_s was the amount of time (4 hours) the columns were pre-soaked before analyses.

Table 7. Mean saturated hydraulic conductivity (K_s) from undisturbed soil profile columns as affected by PAM levels.

PAM Levels	K_s
μg PAM cm^{-3} Soil	mm sec^{-1}
0	1.52 a†
5	1.39 a
10	2.83 b
15	2.59 b

†Means not followed by the same letter are significantly different by LSD ($P<0.05$).

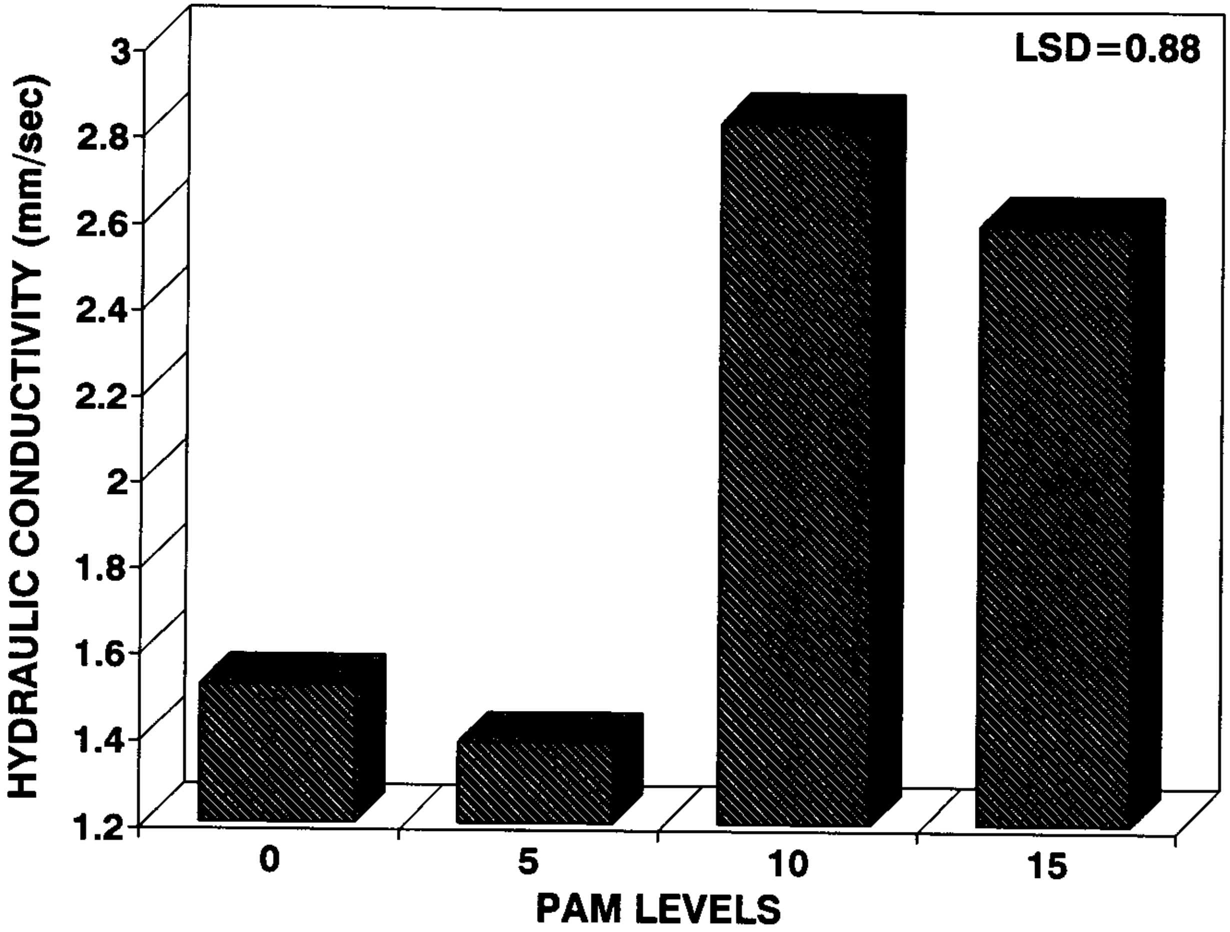

Fig. 7. Mean saturated hydraulic conductivity from undisturbed soil profiles in response to PAM levels (μg PAM cm^{-3} soil).

Experiment 2

Disturbed (tillage-simulated) soil column K_s data were collected. Combinations of PAM levels (0 and 25 mg L^{-1}) and irrigation levels (20, 40, and 60 mm) interacted significantly. The effectiveness of PAM to improve K_s was negligible (Table 8). Average K_s values in response to PAM levels and as a function of irrigation levels are plotted in Figure 8. Untreated columns receiving 20 mm and 40 mm of irrigation perhaps had enough electrolyte to maintain high K_s values. However, at the 60 mm level the K_s values decreased. It is not known why PAM decreased hydraulic conductivity under the lower levels of irrigation, but these low irrigation levels did not wet the entire column.

Table 8. Mean saturated hydraulic conductivity (K_s) from disturbed soil profile columns with two PAM levels and three irrigation levels.

PAM Level	Irrigation level (mm)		
	20	40	60
mg L^{-1}	----------mm sec^{-1}----------		
0	3.14 Aa†	2.75 Ab	2.34 Ac
25	2.32 Ba	2.13 Ba	2.64 Ab

†Within columns, means not followed by the same uppercase letter are significantly different by LSD ($P<0.05$). Within rows, means not followed by the same lowercase letter are significantly different by LSD ($P<0.05$).

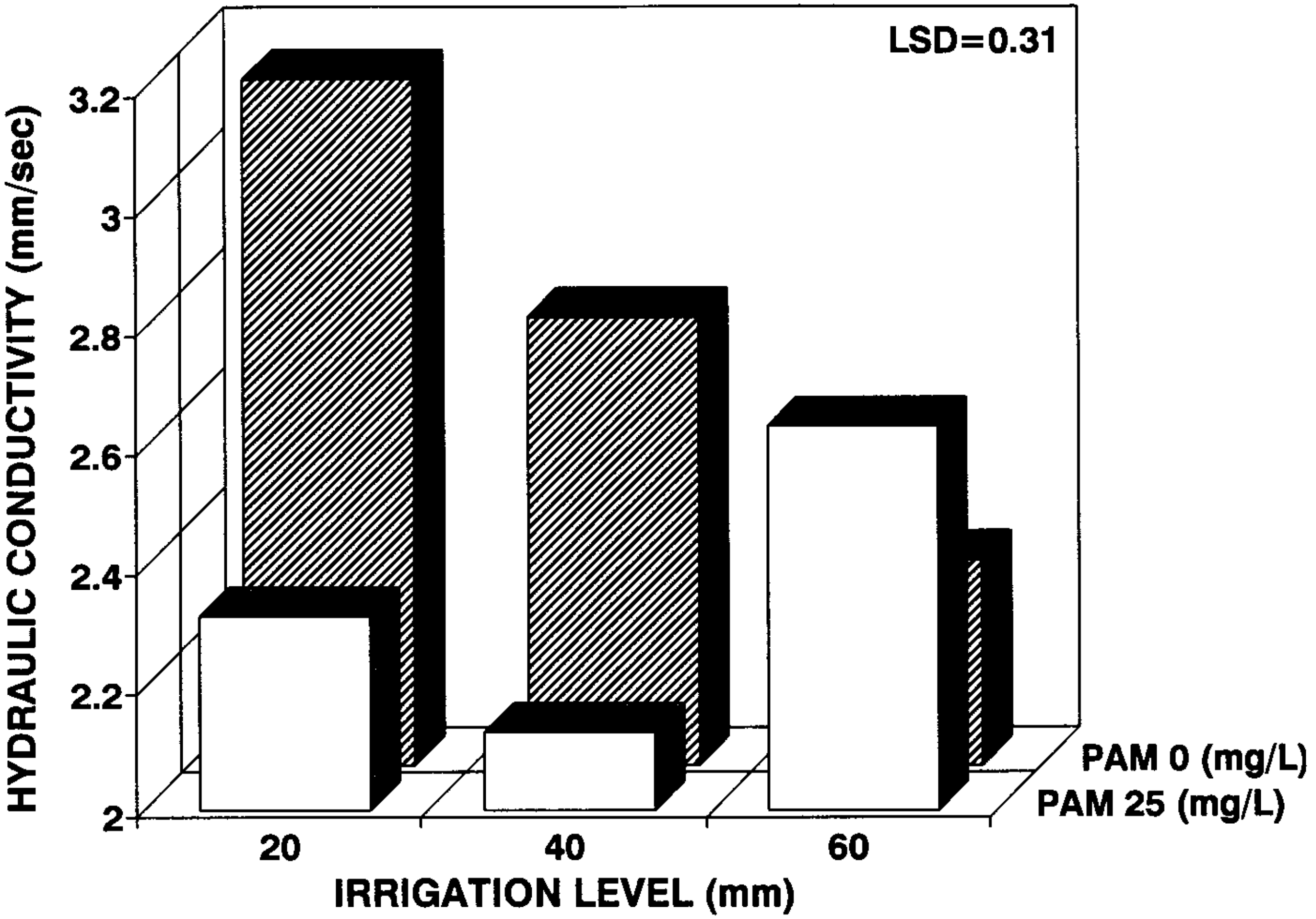

Fig. 8. Mean saturated hydraulic conductivity from disturbed soil profiles as affected by irrigation levels and PAM levels.

CONCLUSIONS

The beneficial use of wastewater for irrigation of crops represents an attractive alternative to disposal. Soil surface penetrometer resistance measurements were not significantly ($P>0.05$) different between treatments. Field saturated infiltration (K_{fs}) rates of PAM-treated plots were approximately double those of the control, and significantly ($P<0.05$) different from non-irrigated plots. The results suggest that wastewater salinity problems on soil permeability can be effectively ameliorated using anionic polyacrylamide polymers. Gypsum also produced a modest beneficial effect in one experiment. Increases in infiltration rates with PAM treatment were expected. However, they are noteworthy in this case because the growing season was relatively rainy, and the infiltration readings were taken months after the last PAM application. The persistence of PAM effects suggests that lower or less frequent applications may also be effective, thereby reducing treatment costs. The ability of PAM to improve K_s in the laboratory columns was variable and not always correlated with levels of polymer added.

REFERENCES

Allison, L.E. 1952. Effect of synthetic polyelectrolyte on the structure of saline and alkali soil. Soil Sci. 73:443-454.

Allison, L.E. 1956. Soil and plant responses to VAMA and HPAN soil conditioners in the presence of high exchangeable sodium. Proc. Soil Sci. Soc. Am. 20:147-151.

Aly, S.M., and J. Letey. 1988. Polymer and water quality effects on flocculation of montmorillonite. Soil Sci. Soc. Am. J. 52:1453-1458.

American Society for Testing and Materials. 1992. ASTM Standard test method for Determination of water content of soil by microwave oven method D 4643 - 87. ASTM, Philadelphia, PA.

Arora, H.S., and N.J. Coleman. 1979. The influence of electrolyte concentration on flocculation of clay suspensions. Soil Sci. 127:134-139.

Ayers, R.S., and D.W. Westcot. 1986. Irrigation water quality criteria. p.3(1)-3(37). In G.S. Pettygrove and T. Asano (eds.). Irrigation with reclaimed municipal wastewater--a guidance manual. Lewis Publishers, Inc. Chelsea, MI.

Ayers, R.S., and D.W. Westcot. 1989. Water quality for agriculture. Irrigation and drainage paper 29. Rev. 1. FAO, Rome.

Bajwa, M.S., and A.S. Josan. 1989. Effect of gypsum and sodic irrigation water on soil and crop yields in a rice-wheat rotation. Agric. Water Manage. 16:53-61.

Ben-Hur, M., J. Faris, M. Malik, and J. Letey. 1989. Polymers as soil conditioners under consecutive irrigations and rainfall. Soil Sci. Soc. Am. J. 53:1173-1177.

Ben-Hur, M., M. Malik, J. Letey, and U. Mingelgrin. 1992. Adsorption of polymers on clays as affected by clay charge and structure, polymer properties, and water quality. Soil Sci. 153:349-356.

Berry, W.L., A. Wallace, and O.R. Lunt. 1977. Recycling municipal wastewater for hydroponic culture. Hortscience 12:186.

Berry, W.L., A. Wallace, and O.R. Lunt. 1980. Utilization of municipal wastewater for the culture of horticultural crops. Hortscience 15:169-171.

Cook, D.F., and S.D. Nelson. 1986. Effects of polyacrylamide on seedling emergence in crust-forming soils. Soil Sci. 141:328-333.

De Boodt, M. 1972. Improvement of soil structure by chemical means. p. 43-55. In D. Hillel (ed.). Optimizing the soil physical environment toward greater crop yields. Academic Press, New York.

Dexter, A. R., and K.Y. Chan. 1991. Soil mechanical properties as influenced by exchangeable cations. Soil Sci. 42:219-226.

El-Morsy, E.A., M. Malik, and J. Letey. 1991. Polymer effects on the hydraulic conductivity of saline and sodic soil conditions. Soil Sci. 151:430-435.

Elrick, D.E., and W.D. Reynolds. 1992. Infiltration from constant-head well permeameters and infiltrometers. p. 1-24. In G.C. Topp et al. (eds). Advances in measurement of soil physical properties: Bringing theory into practice. Soil Science Society of America, Madison, WI.

Gardiner, D.T., G. Quezada-Garcia, and P.L. Connor. 1991. Irrigating peppers with high-sodium wastewater. p. 331. In Agronomy abstracts. American Society of Agronomy, Madison, WI.

Hagin, J, and G.B. Bodman. 1954. Influence of the polyelectrolyte CRD-186 on aggregation and other physical properties of some California and Israeli soils and some clay minerals. Soil Sci. 78:367-378.

Harris, R.F., G. Chester, and O.N. Allen. 1966. Soil aggregation. In A.G. Norman (ed). Advances in Agronomy 18:107-160.

Hendershot, W.H., H. Lalande, and M. Duquette. 1993. Soil reaction and exchangeable acidity. p. 141-166. In M.R. Carter (ed.). Soil sampling and methods of analysis. Canadian Soc. of Soil Sci. Lewis Publishers, Chelsea, MI.

Hillel, O. 1982. Introduction to soil physics. p.101. Academic Press, San Diego, CA.

Janzen, H.H. 1993. Soluble salts. p.161-166. In M.R. Carter (ed.). Soil sampling and methods of analysis. Canadian Soc. of Soil Sci. Lewis Publishers, Chelsea, MI.

Kazman, Z., I. Shainberg, and M. Gal. 1983. Effect of low levels of exchangeable sodium and applied phosphogypsum on the infiltration rate of various soils. Soil Sci. 135:184-192.

Keren, R., and I. Shainberg. 1981. Effect of dissolution rate on the efficiency of industrial and mined gypsum in improving infiltration of a sodic soil. Soil Sci. Soc. Am. J. 45:103-107.

Klute, A., and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. p. 687-734. In A. Klute (ed.). Methods of soil analysis, Part 1. Soil Science Society of America, Madison, WI.

Martin, W.P., G.S. Taylor, J.C. Engibous, and E. Burnett. 1952. Soil and crop responses from field applications of soil conditioners. Soil Sci. 73:445-472.

Martin, W.P. 1953. Status report on soil conditioning chemicals. I. Proc. Soil Sci. Soc. Am. 17:1-8.

Martin, J.P., W.P. Martin, J.B. Page, W.A. Raney, and J.D. Dement. 1955. Soil Aggregation. Adv. Agron. 7:1-37

Mitchell, A.R. 1986. Polyacrylamide applications in irrigation water to increase infiltration. Soil Sci. 141:353-358.

Nadler, A., and M. Magaritz. 1986. Longterm effects of extensive gypsum amendment applied with sodic water irrigation on soil properties and soil solution chemical composition. Soil Sci. 142:196-202.

Oster, J.D., and F.W. Schroer. 1979. Infiltration as influenced by irrigation water quality. Soil Sci. Soc. Am. J. 43:444-447.

Oster, J.D., and H. Frenkel. 1980. The chemistry of the reclamation of sodic soils with gypsum and lime. Soil Sci. Soc. Am. J. 44:41-45.

Oster, J.D., and J.D. Rhoades. 1986. Water management for salinity and sodicity control. p.7(1)-7(20). In G.S. Pettygrove and T. Aasano (eds.). Irrigation with reclaimed municipal wastewater--a guidance manual. Lewis Publishers, Inc., Chelsea, MI.

Rhoades, J.D., D.B. Krueger, and M.J. Reed. 1968. The effect of soil mineral weathering on the sodium hazard of irrigation waters. Soil Sci. Soc. Amer. Proc. 32:643-647.

Rhoades, J.D. 1968. Mineral-weathering correction for estimating the sodium hazard of irrigation water. Soil Sci. Soc. Amer. Proc. 32:648-652.

Rhoades, J.D. 1972. Quality of water for irrigation. Soil Sci. 113:277-284

Sanderson, K.C. 1986. Introduction to the workshop on wastewater utilization in horticulture. Hortscience 21:23-23.

Shainberg, I., and J.D. Oster. 1978. Quality of irrigation water. International irrigation center. IIIC Publication No. 2 International Irrigation Information Center. Volcani Center, Bet Dagan, Israel.

Shainberg, I., J.D. Rhoades, and R. J. Prather. 1980. Effects of low electrolyte concentrations on clay dispersion and hydraulic conductivity of sodic soil. Soil Sci. Soc. Am. J. 45:273-277.

Shainberg, I., R. Keren, and H. Frenkel. 1982. Response of sodic soil to gypsum and calcium chloride applications. Soil Sci. Soc. Am. J. 46:113-117.

Shainberg, I., and J. Letey. 1983. Response of soils to sodic and saline conditions. Higardia 52:1-57.

Shainberg, I., D.N. Warrington, and P. Rengasamy. 1990. Water quality and PAM interactions in reducing surface sealing. Soil Sci. 149:301-307.

Sheldrick, B.H., and C. Wang. 1993. Particle size distribution. p. 499-511. In M.R. Carter (ed.). Soil sampling and methods of analysis. Canadian Soc. of Soil Sci., Lewis Publishers, Inc. Chelsea, MI.

Sherwood, L.V., and L.C. Engibous. 1953. Status report on soil conditioning chemicals. II. Proc. Soil Sci. Am. 17:9-16.

Suarez, D. L., J.D. Rhoades, R. Lavado, and C.M. Grieve. 1984. Effects of pH on saturated hydraulic conductivity and soil dispersion. Soil Sci. Soc. Am. J. 48:50-55.

U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkaline soils. U.S. Agric. Handbook 60. U.S. Government printing office, Washington, DC.

Wallace, A., G.A. Wallace, and A.M. Abouzamzam. 1986a. Interaction of soil conditioner with other limiting factors to achieve high crop yields. Soil Sci. 141:343-345.

Wallace, A.G., A. Wallace, and A.M. Abouzamzam. 1986b. Amelioration of sodic soils with polymers. Soil Sci. 141:359-362.

Wallace, A., G.A. Wallace, and A.M. Abouzamzam. 1986c. Effects of excess levels of a polymer as a soil conditioner on yield and mineral nutrition of plants. Soil Sci. 141:377-380.