The effects of gypsum rates and irrigation regimes on soil physical and chemical properties of a saline-alkali soil
by Douglas John Dollhopf

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in SOILS
Montana State University

Abstract:
The effects of gypsum rates (0-5-10 T/A) and irrigation frequency (5-10-15 days) on soil physical and chemical properties of a saline-alkali soil were evaluated.

An evaluation of the effects of these treatments on soil crusting indicated gypsum rates (5 and 10 T/A) significantly reduced crust strength within the surface two inches. After irrigation over the gypsum, crust strength was significantly reduced to a tested depth of six inches, and the 10 T/A rate was significantly more effective than the 5 T/A rate. Also, irrigation had a significant effect in reducing crust strength which was attributed to the leaching out of salts resulting in a decreased SAR.

The swelling and shrinking ability of this saline-alkali soil was decreased most effectively by the 5-day irrigation frequency in conjunction with gypsum treatments. This' was attributed to the' replacement of Na by. Ca' on the- soil exchange complex.

-The rate- of infiltration- and quality of water moving through the surface' six inch soil mass was increased with- gypsum treatments resulting in an increased leaching efficiency. The 10 T/A rate was consistently more effective than the- 5 T/A rate.

Preliminary laboratory measurements on- hydraulic conductivity and water flux with undisturbed field cores indicated a saturated gypsum solution increased the hydraulic properties of' this soil by as much as 246%.

Hydraulic conductivity and water- flux were calculated within the undisturbed soil- profile at various times during irrigation and drainage. These data indicate gypsum- consistently increased the hydraulic properties of1the profile and the 10 T/A rate appeared to be more effective than- the 5 T/A rate.

Soil chemical analysis data indicated the; measured increases in soil hydraulic properties had the- effect of removing large quantities of- excess salts, but one summer of gypsum and irrigation treatments did not reduce the- high saline-alkali status to acceptable levels for good crop growth. However, the decreases in SAR and- EC due to 10 T/A- gypsum and the 5-day irrigation frequency implies another summer of such treatments could reduce the saline-alkali condition to tolerable levels for good crop production.

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Date May 27, 1971

THE EFFECTS OF GYPSUM RATES AND IRRIGATION REGIMES ON SOIL PHYSICAL AND CHEMICAL PROPERTIES OF A SALINE-ALKALI SOIL

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ABSTRACT

The effects of gypsum rates (0-5-10 T/A) and irrigation frequency (5-10-15 days) on soil physical and chemical properties of a saline-alkali soil were evaluated.

An evaluation of the effects of these treatments on soil crusting indicated gypsum rates (5 and 10 T/A) significantly reduced crust strength within the surface two inches. After irrigation over the gypsum, crust strength was significantly reduced to a tested depth of six inches, and the 10 T/A rate was significantly more effective than the 5 T/A rate. Also, irrigation had a significant effect in reducing crust strength which was attributed to the leaching out of salts resulting in a decreased SAR.

The swelling and shrinking ability of this saline-alkali soil was decreased most effectively by the 5-day irrigation frequency in conjunction with gypsum treatments. This was attributed to the replacement of Na by Ca on the soil exchange complex.

The rate of infiltration and quality of water moving through the surface six inch soil mass was increased with gypsum treatments resulting in an increased leaching efficiency. The 10 T/A rate was consistently more effective than the 5 T/A rate.

Preliminary laboratory measurements on hydraulic conductivity and water flux with undisturbed field cores indicated a saturated gypsum solution increased the hydraulic properties of this soil by as much as 246%.

Hydraulic conductivity and water flux were calculated within the undisturbed soil profile at various times during irrigation and drainage. These data indicate gypsum consistently increased the hydraulic properties of the profile and the 10 T/A rate appeared to be more effective than the 5 T/A rate.

Soil chemical analysis data indicated the measured increases in soil hydraulic properties had the effect of removing large quantities of excess salts, but one summer of gypsum and irrigation treatments did not reduce the high saline-alkali status to acceptable levels for good crop growth. However, the decreases in SAR and EC due to 10 T/A gypsum and the 5-day irrigation frequency implies another summer of such treatments could reduce the saline-alkali condition to tolerable levels for good crop production.

INTRODUCTION

The adverse effects of high salt (saline) and high sodium (alkali) in a soil system are present in many arid and semi-arid regions of the world. According to Clark (18), Montana alone has 150,000 acres of farm lands so affected.

These adverse effects upon crop growth are two-fold. First, the high sodium level causes adverse physical properties in these soils. Among other things these soils form hard surface crusts upon drying, thereby decreasing seedling emergence by as much as 100%. Upon wetting these soils swell causing closure of the water transmitting pores, consequently, the downward movement of water is retarded making reclamation of the saline soil profile doubtful. Second, the saline nature of the soil profile causes plant growth problems and plant-water-stress problems. In this case, the roots of a seedling may be in a zone of high moisture yet suffer the effects of wilting due to the adverse osmotic potential caused by high salts in the soil.

Successful management of these soils requires reclamation. An economic technique is required to improve physical properties and to keep the water transmitting soil pores open upon wetting. Once the water transmitting ability of the soil profile is increased an efficient program of irrigation and drainage can be used to leach out the excess salts.

Numerous investigators (3,7,9,33,48) have tested various chemical amendments on saline-alkali soils, however, gypsum ($CaSO_4.2H_2O$)

appears to be the most economically feasible amendment.

Only within the past decade have equipment and techniques been developed to measure, in a rapid and comprehensive manner, the unsaturated movement of water through the undisturbed field soil profile. Such techniques are only beginning to be utilized for evaluating field agricultural oriented problems.

The objectives of this study were:

1) To investigate the effects of gypsum upon unsaturated water movement rates through a saline-alkali soil profile.

2) To investigate the effects of irrigation frequency upon leaching efficiency.

3) To investigate the changing chemical status of the soil profile with gypsum and irrigation treatments.

4) To investigate the effects of gypsum and irrigation frequency upon soil crusting.

This work was conducted on a saline and alkali soil in the Yellowstone Valley of Montana.

LITERATURE REVIEW

Clays and Double Layer Theory

In a soil-system the clays, ignoring organic matter, compose the active fraction. Three factors control swelling and shrinking in clays which cause the physical problems associated with saline and alkali soils. These three factors are clay particle size, clay type or structure, and clay-cation status.

Different clays vary on the average in physical size; the smaller the particle size the greater is the attraction to water which results in a greater tendency to swell and shrink. Therefore, not only is the amount of clay important, but also the particle size. Montmorillonite clay, is on the average, smaller than kaolinite or illite clays and montmorillonite has a greater swell-shrink capacity.

Montmorillonite and illite are classified as 2:1 lattice clays and kaolinite is classified as a 1:1 lattice clay. Because of the strong oxygen-hydroxyl linkages in the 1:1 lattice clays they expand little upon wetting. Such a linkage is not present in 2:1 clays and they expand more freely when wetted. Saline and alkali soils are generally dominated by 2:1 clays.

These first two controlling factors in clay swelling and shrinking cannot be regulated in the field since they are inherent characteristics of the soil. But swelling and shrinking due merely to the inherent clay characteristics is not usually the major problem with saline-alkali soils. The clay-cation status, then, is what renders thousands of acres of potentially productive land in arid regions presently unproductive.

The physical properties resulting from cation-clay-water interaction is best predicted by Gouy-Chapman diffuse layer theory (29). This proposes that a swarm of sodium ions upon a single negatively charged clay particle surface will diffuse out a greater distance from the clay particle than a similar swarm of calcium ions. This phenomena can be attributed to the physical properties of these ions, chiefly, the ionic charge and the size of the cations. A system, then, of two clay particles each with a diffuse layer of cations extending out towards the other clay particle provides the working model. An overlapping layer, formed by two diffuse layers, may or may not form depending on the distance the diffuse layer extends from the clay surface which is a function of the physical status of the cation, and the distance between the clay particles. It so happens that Na fabricates a thick diffuse layer and Ca a much thinner one. This means that two sodium dominated clay particles will tend to have overlapping diffuse layers, whereas, the thinner diffuse layer of Ca does not form this overlapping layer as readily. Osmosis predicts that water movement through a semi-permeable membrane is from a solution of low osmotic pressure (low salt concentration), to a solution of high osmotic pressure (high salt concentration). In soils one does not have a membrane, but the system acts as if a membrane were present. An overlapping layer, as often occurs in a sodium dominated system increases the osmotic pressure of the solution between clay particles relative to the bulk solution. In a Ca dominated system there is usually much less overlapping of cation swarms and thus, a much lower osmotic pressure. When non-saline water is applied to these two different clay-cation systems water is pulled into the zone between the sodium dominated clay particles due to the osmotic pressure gradient, creating a pressure which swells and disperses the clay particles. The calcium dominated clay will take on water and swell, but the magnitude of this event is much smaller. Swelling and dispersion of the clays within the soil system leads to destruction of soil aggregates, closure of the pores, and renders water movement extremely slow.

Saline-alkali soils typify the above described phenomena. For successful crop growth such soils require the removal of excess salts by leaching. However, when water is applied for leaching, the alkali condition causes swelling, thereby, closing the soil pores and reducing the downward flux of water to the extent that leaching of excess salt ceases. The first phase in reclaiming saline-alkali soils, which is the essence of the problem, is to increase the ability of the soil to transmit greater quantities of water through its profile. The following investigations support diffuse layer theory mechanisms of clay-cation interaction which forms the basis of approach to reclamation of saline-alkali soils.

Interaction of Salts and Clays Upon Water and Ion Movement

Most of the studies on water movement in soils with respect to salts have been conducted in saturated systems. It appears that very few studies have been made on the influence of salts on unsaturated flow. An understanding of how unsaturated water flow is influenced by clay type, exchangeable ions, soluble salts, and water quality is essentially in reclamation projects.

Fireman (24), Quirk and Schofield (56) studied the effect of exchangeable ions on saturated permeability. Both investigations indicated with low eletrolyte concentration in water, saturated permeability decreased as exchangeable sodium increased. Fireman (24) found that the permeability of a sandy loam soil was initially high with water containing 4,500 ppm sodium chloride but decreased with time as swelling occurred. However, Quirk and Schofield (56) found that waters containing greater than 14,500 ppm sodium chloride maintained high permeability in sodium soils. In this case the osmotic pressure gradient was from within the overlapping diffuse layers to the surrounding pores that held the added external solution, therefore water moved out of the diffuse layer system leaving a flocculated clay system. Quirk and Schofield concluded that it should be possible to maintain the permeability of a soil irrespective of the degree of sodium saturated by using sufficiently strong electrolyte solutions or by the addition of gypsum or other soluble calcium salts to the irrigation rates. This would have the effect of depressing the diffuse layer system due to the physical status of the calcium ion.

Reeve and Bower (57) investigated the use of high-salt waters as a flocculant and source of divalent cations for reclaiming sodic soils. They found high salt waters which kept the diffuse layer system depressed allowed faster reclamation of sodic soils. When more diluted salt solutions were used the system began to swell and reclamation was retarded.

Aggregate stability, as affected by salts, has an influence on the permeability of a soil. Collis-George and Smiles (19) found that as sodium content increased, the total cation concentration in suspension that was required to maintian aggregate stability also increased. Rowell (63) studied the swelling of Na and Ca dominated montmorillonite clay and concluded that swelling depended on the activity ratio $\frac{Na}{\sqrt{Ca}}$ and on total electrolyte concentration. As the activity ratio increased, the proportion of the aggregates that deflocculated increased. The flow of water can be expected to be reduced when deflocculation occurs because pore size is reduced.

Fireman and Bodman (23) found greater permeability in a clay loam soil containing predominately kaolinitic clay than on another containing predominately montmorillonitic clay. Initial permeability values of these two soils with distilled water was similar, the diffuse double layer was still depressed, but as time progressed the permeability decreased more rapidly in the soil containing montmorillonitic clay which can be attributed to expansion of the diffuse layer system.

Diffusivity is a characteristic of the soil which describes the tendency of a soil to conduct water in the unsaturated state (11). Gardner et. al. (27) measured water movement in two soils with various exchangeable sodium to calcium ratios. They found that when the exchangeable sodium percentage (ESP) was above 25, the diffusivity was reduced as much as one-thousand fold when the electrolyte concentration was decreased from 300 to 3 me/L. They also found that diffusivity increased as the electrolyte concentration increased, regardless of the ESP, which can be attributed to a depressing of the diffuse layer system. Christenson (17) found that diffusivity was increased by a factor of two or more with .015 N $CaCl_2$ over distilled water in illite and dickite soils adjusted to a sodium-adsorption-ratio (SAR) 0 and SAR 40, and with monmorillonite soil with SAR 0. This electrolyte concentration did not depress the diffuse layer system or reduce swelling sufficiently with the montmorillonite soil SAR 40 to increase diffusivity by an appreciable amount. Diffusivity was greater at a particular moisture content for the dickite soil than for the illite soil and greater for the illite soil than for the montmorillonite soil, which can be attributed to the inherent swelling characteristics of these clays. An electrolyte concentration of

.015 N $CaCl_2$ was effective in reducing the swelling to a negligible amount on illite and montmorillonite soils with SAR 0. This concentration failed to reduce the effect of swelling more than slightly on these soils with an SAR 40.

McNeal (42,43,44) evaluated the effects of salts and clays upon hydraulic conductivity of a soil. He found that the relative hydraulic conductivity decreased markedly with increasing clay content and replacement of Ca with Mg and Na. Hydraulic conductivity decreased with decreasing electrolyte concentration and increasing sodium-adsorption-ratio (SAR) of the percolating solution. The decreases were particularily pronounced for soils high in 2:1 layer-silicates; however, hydraulic conductivity of 1:1 layer silicates was virtually insensitive to variations in solution composition. The decreases were largely irreversible upon the reapplication of high salt or high Ca solutions to the soil, except those soils containing greater than 10% montmorillonite on a whole-soil basis, because, here, the diffuse layer system could be depressed. He states that swelling of the soil colloids and subsequent closing of conducting pores followed by particle dispersion is responsible for decreases in hydraulic conductivity in the presence of low salt, high Na solutions, and concludes that restoration of soil structure in sodic soils requires both high calcium conditions and wetting-drying cycles.

Martin et. al. (40) investigated the relationship of exchangeable sodium percentage(ESP) at different soil pH levels to hydraulic conductivity. They found highly significant negative correlation coefficients relating hydraulic conductivity to ESP.

There is an indication by some investigators that distilled water, if applied in large enough quantities will remove exchangeable sodium from saline soils (4). From a practical standpoint this is not feasible. First, when soils containing soluble alkaline salts are leached with rain water, permeability decreases to an unacceptable rate with time. Second, few soils have an internal drainage system capable of handling the vast quantities of distilled water that would have to be applied in a relatively short period of time. Bower and Goertzen (10) demonstrated that water containing calcium from gypsum sources removed sodium with greater ease than distilled water.

These investigations support the diffuse layer phenomena, that depressing the diffuse layer system induces soil flocculation and promotes reclamation of soils. Once this phenomena was established investigators approached the reclamation of saline and alkali soils by searching for effective soil amendments.

Gypsum as a Soil Amendment

Numerous studies [Fitts et al. (25), Overstreet et al. (52, 53,), Padhi et al. (54)] comparing gypsum to sulfur, sulfuric acid, calcium chloride, organic matter, soil conditioners, starch, etc. have concluded varying results. These varying results can be attributed to differences existing within the experimental site and in a few investigations non-equivalent rates of treatments were applied. For example, Fitts et al. (25) found sulfur more effective than gypsum treatments when equal pounds per acre were applied. Assuming sufficient amounts of $CaCO_3$ are present in the soil for the sulfur reaction, a genuine comparison of the Ca supplying ability of these amendments requires about 5 tons of gypsum to one ton of sulfur (65). However, many investigators found positive results with gypsum. Padhi et al. (54) evaluated the effects of gypsum and starch on water movement and sodium removal from solonetzic soils. Their results indicate soil disturbance in conjunction with appropriate treatment, especially with gypsum, increased water percolation and sodium removal. Starch was not effective, however,

Van Schaik (69) found that permeability of a montmorillonite dominated soil was negligible when the exchangeable sodium percentage (ESP) exceeded 15 to 20. The same soil with a gypsum treatment had a relatively higher permeability at ESP up to 30 to 35. Pair and Lewis (55) applied 10 and 20 tons per acre gypsum on slick spots and evaluated chemical and water intake-rate changes. The water intake rate increased from .01- to .10- and .22-inches per hour with 10 and 20 tons of gypsum per acre, respectively. Salt removal with gypsum was directly correlated with intake rates and both treatments decreased the ESP.

Amemiya et al. (3), Boawn (9), Kelly and Brown (33) and other investigators have studied reclamation process of saline and alkali soils. Results of such studies have often varied due to the influence of climate, geological, and soil variability.

During the 1950's and early 1960's a longterm study in the Yellowstone Valley of Montana evaluated techniques of reclaiming salty soils (48). The results of this investigation are of particular importance since the soil forming processes and climate are nearly identical to the experimental site of this study, which is also in the Yellowstone Valley. The purpose of the study was three fold; to evaluate 1) leaching and organic matter treatments in conjunction with gypsum rates of 0-10-20 tons per acre, 2) chemical amendments, and 3) leaching methods.

In the first case, 90 days of leaching significantly decreased electrical conductivity and soluble sodium, but no significant effect due to the manure treatment was found. However, by the fifth year, the salt status of plots which underwent normal irrigation with cropping was not significantly different from plots leached 90 days. After these five years, plots with gypsum, both 10 and 20 tons per acre, had a highly significant decrease in both soluble sodium and electrical conductivity. However, this significant effect due to gypsum was on unleached plots and no explanation could be given why leaching plots did not respond to gypsum. Five years after the initial 90 day leaching treatment a second leaching treatment of 117 days decreased salt levels in all plots to an acceptable level for crop growth, including plots with no gypsum or manure treatments. This last statement implies reclamation was possible with irrigation only.

The second aspect of the above reclamation study evaluated numerous chemical amendments to determine their relative effectiveness for replacing sodium during the reclamation process. Treatments consisted of gypsum rates, sulfur, sulfuric acid, calcium chloride, sugar beet waste lime, soil conditioners and aluminum sulfate. After all plots were leached for 90 days no significant differences between chemical amendments were present.

The third aspect of the study evaluated methods of leaching. The treatments were:

1) check-not leached-barley + sweetclover + irrigation
2) cropping (barley) + fall leaching
3) alternate flooding and drying (2-week frequency)
4) continuous leaching
5) continuous leaching + cropping (rice)

6) spring leaching + cropping (grass)

7) continuous leaching + cropping + subsoiling (18 inches)

8) spring leaching + cropping + subsoiling (18 inches)

The results indicate all treatments significantly reduced electrical conductivity at all depths compared to the check, however it was noted alternate flooding and drying for two week periods removed salts most effectively as indicated by a lower salt level in four out of the five depths tested. Neither subsoiling nor the presence of plants growing in the flooded plots increased salt removed, however, plots cropped during part of the season had less salt removed at the lower depths than those plots flooded all season. These results indicate that, with the exception of alternate leaching (treatment 3), the major differences in leaching treatments was the length of time the plots were flooded; salt removal increased as the volume of water moving through the soil profile increased.

Thus, the literature on clay-salt interaction and gypsum investigations indicate gypsum aids in removal of salts and has been observed to increase infiltration on saline and alkali soils. However, the actual field reclamation mechanism of increased hydraulic conductivity and water flux within the soil profile due to gypsum has not been evaluated. Such an evaluation has not been possible until recent years due to the difficulty in measuring soil hydraulic properties in the field.

Measurement of Soil Hydraulic Properties

Because of the complexity of soil-water movement, particularly under heterogeneous conditions in the field, relatively few studies have been analyzed to the same degree as laboratory experiments. Generally, early field investigations were complicated by the presence of an actively growing crop and only included measurements of soil water in the evaluation of consumptive use or irrigation efficiencies. When no crop was actively growing efforts were usually made to evaluate water infiltration and storage in the profile with some estimation of evaporation and deep percolation. Most of the work during the past decade has been directed toward an improved understanding of the effects of hydraulic conductivity, soil-water characteristics, and potential gradient upon water flow in the field soil profile.

Laboratory determined values of hydraulic conductivity have been used to calculate or predict water movement in field soils. Miller and Bunger (45) used both tensiometers and a neutron meter to determine the soil-water characteristics at several depths within natural and artificially produced layered soils. Unsaturated conductivity curves were determined on disturbed soil samples by a steady state outflow procedure with hanging water columns used to obtain total suction and suction gradients. Green et al. (30) using laboratory determined values of hydraulic conductivity, predicted water movement in naturally layered soils. Their approach consisted of solving

$$\frac{d\theta}{dt} = \frac{d}{dx}\left(\frac{KdH}{dx}\right) \qquad [1]$$

where θ is the volumetric water content, K is the hydraulic conductivity, H is the total hydraulic head (the algebraic sum of the suction and gravity heads), x is the vertical distance, and t is time.

Tensiometers have been used extensively to study water movement [e.g. Connell and Stolzy (14); Haise *et al.* (31); La Rue *et al.* (36); Marshall and Stirk (39); Richards (61); Richards and Neal (59)]. In these investigations, tensiometer use was primarily directed toward measuring hydraulic gradients existing during infiltration or during periods of drainage following infiltration. In most cases, rates of water movement were inferred from Darcy's equation

$$F = -K \nabla \Phi \qquad [2]$$

where F is the flux, K is the hydraulic conductivity, and $\nabla\Phi$ is the total hydraulic head gradient. With the tensiometer data soil layers responsible for restricted water movement were readily identified, although values of hydraulic conductivity could not generally be calculated owing to lack of information on water content changes.

Field measurements of hydraulic conductivity have been made by Richards *et al.* (62) and Ogata and Richards (51) using tensiometers and gravimetric soil-water content data. Measurements were made in the surface 50 cm of a sandy loam after a heavy irrigation with surface evaporation prevented in the latter study. The hydraulic conductivity values calculated from the field data were found to be in agreement with values obtained previously in the laboratory.

Investigations by van Bavel _et al_, (67,68), Brust _et al_. (12), Nielsen _et al_. (49), La Rue _et al_. (36), and Davidson _et al_. (20) have determined values of K (h) at different depth intervals within field soil profiles. These investigations used tensiometers to measure hydraulic gradients during periods of soil-water redistribution. Brust _et al_. and van Bavel _et al_. used an Am-Be source of fast neutrons to measure water content changes while Nielsen _et al_. and La Rue _et al_. used soil-water characteristics curves derived from soil cores to relate tensiometric values to soil-water content values. The latter investigators found that estimates of soil-water content can be made with tensiometers with the same degree of accuracy as that obtained with gravimetric sampling. However, the desorption curves made from soil cores represent desorption only while both desorption and sorption occur in the field. Davidson _et al_. attempted to measure the hydraulic properties and predict soil-water flux within the various depths of a profile by using the two equations derived by Gardner (1962) and Block _et al_. (1969)

$$K = K_o \exp[a\ (\theta - \theta_o)] \qquad [3]$$

and

$$v_L = K_o/(1 + aK_o\ t/L) \qquad [4]$$

where K is the hydraulic conductivity, v_L is the soil water flux, L is the length of the drainage profile, θ is water content, t is time, a is a constant, and subscript zero refers to water saturation. Because there is no soil-water potential gradient within these equations, no tensiometers would be needed in the field. However, the ability of these equations to predict accurate flux and hydraulic conductivity depends on two assumptions; first, the profile must approach a unit hydraulic gradient during drainage, second, all the profile depths must drain nearly uniformly. Davidson tested three soils varying from a homogeneous to a heterogeneous profile. The above equations predicted hydraulic conductivity and flux for the homogeneous and the intermediate soils, but not for the soils with heterogeneous profile. Also, these measurements were not complicated by the presence of a water table. It appears, then, that the above equations could be used for the seldom met field conditions of a homogeneous soil with a very deep water table.

All these investigations illustrate that K (θ) or K (h) may be calculated directly from field measurements. That such measurements can be made outside the laboratory and in the undisturbed field, places more reliability on the data. The principle disadvantages of the field determination are the small range in water contents obtained at the greater depths, and the fact that values of hydraulic conductivity are restricted to soil-water pressures within the tensiometer range.

Analyses of soil-water movement during the growth of a crop have been limited to a few, small experimental sites where soil-water properties and changes in soil-water content have been measured intensively with soil depth. Investigations by van Bavel *et al.* (67,68) utilizing field methods of describing the hydraulic properties of soils, have measured flux of water within soil profiles as a function of time and soil depth under an actively growing crop.

LaRue *et al.* (36) using field measured values of K (θ) calculated the soil-water flux at 180 cm below the surface of Yolo loam uniformly cropped to common rye grass. Although the same total quanitity of water was applied to all plots, the treatments included irrigations of 4, 8, and 16 cm of water applied at intervals of approximatley 1, 2, and 4 weeks, respectively. All plots were initially at similar moisture contents. Their data indicates irrigating frequently with small applications of water allowed a greater quantity of water to pass through and below the root zone. These data show, then, that the amounts of water moving past the root zone are influenced by irrigation frequency. Such findings are very important in reclamation of saline and alkali soils when excess salts need to be leached out.

Leaching and Displacing the Soil Solution

The ability to predict changes in the soil solution concentration during infiltration and drainage has not been completely accomplished. Bigger and Nielsen (6) found for soil-water contents less than saturation, but greater than those equivalent to 1/5 bar, both laboratory and field data show leaching efficiencies to be greater than those for saturated conditions. This suggests that leaching soils at a water content below saturation could produce more efficient leaching and thereby reduce the amount of water required as well as reduce drainage problems in areas of high water tables. Wilson and Luthin (70) found that rainfall leached salts from a diatomaceous earth soil more efficiently than larger quantities of water applied by ponding. In an experiment established on Levis silty clay soil classified as moderately alkali and high in salts, Nielsen et al. (50) compared leaching by ponding and intermittent sprinkling. The latter treatment applied the water in such a manner that the intake rate exceeded the application rate, thus avoiding ponding on the surface. The plots were covered to minimize evaporation. Under these conditions it was found that 26.2 cm of water applied by sprinkling reduced the salt content of the upper 30 cm to the same degree as 74.9 cm applied by continuous ponding.

Miller et al. (46) made a study of how solutes move through a Panoche clay loam profile. A comparison was made of the movement of a surface-applied chloride salt under two methods of water application, continuous ponding and intermittent 5-cm applications which occurred about once a week. On the average the soil-water content under intermittent ponding was .06 $cm^3 \cdot cm^{-3}$ less than the continuous ponding treatment which approached saturation. Also, the average flow rate for the intermittent treatment was an order of magnitude less than that for continuous treatment. The results indicated that leaching was more efficient under the unsaturated and relatively slow flow rate conditions.

Thus, leaching soils under unsaturated conditions brings about the following changes, 1) decreases the relative volume of water passing through larger pores, thereby, decreasing future drainage problems, and 2) increases the mixing within soil pores caused by molecular diffusion associated with generally smaller flow velocity values, thereby, increasing leaching efficiency.

The above discussion implies that saline and alkali soils need not be leached by continuous ponding. Instead, frequent irrigations with a growing crop may leach out salts as well as continuous ponding, and such a program is more feasible to a farmer.

The analysis of soil hydraulic properties as a function of clay-salt interactions is highly important in the reclamation process, however, a phenomenon occurring within the top one inch of the profile is often the most limiting aspect of saline and alkali soils, that of soil crusting.

Surface Crusts and the Modulus of Rupture Technique

Modulus of rupture is a measure of the breaking strength of materials, and is defined as the maximum fiber stress, ie., force per unit area, that a material will withstand without breaking. Modulus of rupture studies on artificial briquets implies two assumptions: 1) that the physical properties of the artificial briquets are similar to those of natural crusts, and 2) that the modulus of rupture is a good indication of the force exerted by seedlings in breaking natural crusts. However, the validity of the modulus of rupture was questioned because it measures only a soil property and is not related to crust thickness or seed spacing. It was thought seedling emergence might be influenced by crust thickness because, for a given unit crust strength, the force required to break a crust depends upon its thickness. It was also expected that seedling emergence might be influenced by seed spacing because closely spaced seeds might break through a stronger crust than seeds spaced further apart. Hanks and Thorp (32), however, found no evidence indicating wheat seedling emergence is directly influenced by either seed spacing or crust thickness. They believed emergence of a wheat seedling through a crust is influenced by the strength of the crust immediately around the growing apex and not by the strength of the entire crust. This suggests that seedlings do not "press" on the crust until it breaks but rather must worm their way through the entire crust. A seedling, then, exerts a nearly constant moving force through the crust thickness.

Modulus of rupture seems to be the most reliable method for evaluating the crusting problem of soils. Gerard (28) found that strength of briquets increases 1) with decreasing soil moisture; 2) with increasing silt and clay and exchangeable Na^+ content; and 3) with slow drying. It was suggested that slow drying of soils, even when high concentrations of divalent ions are present, such as with gypsum treatments, increased the soil strength due to the better distribution and orientation of soil particles, especially the silt and clay particles. Therefore, slow drying causes greater close packing of soil particles which enhance crust formation. On the contrary, fast drying decreased crust strength due primarily to the fact that soil particles do not have time to be re-arranged before becoming dry and immobile. On semi-arid irrigated agricultural lands high in Na, such a factor as soil drying rate after irrigation could be a means of surface crust management.

Soil physical characteristics such as texture, structure, puddling, and bulk density have been correlated to modulus of rupture measurements. Allison (1) used the modulus of rupture technique as an index to soil structure. Lutz and Pinto (38) pointed out that crusts form on soils of almost any textural condition except coarse sand with an extremely low silt and clay content. The literature demonstrates some disagreement in predominance of particle size, either silt or clay, in crusted topsoils. Stauffer (64) concluded that the relationship between mechanical composition of the soil and its modulus of rupture appeared to be linear; that is the greater the clay content the greater the modulus of rupture. Carnes (15) found that the modulus of rupture was proportional to the surface area of the fine particles present, which implies a predominance of clay over silt would form a harder crust. Chepil (16) found the modulus of rupture varies inversely with the diameter of the mechanical separates from which the briquets are formed, and this again follows the concept that clay promotes crusting over silt. However, other researchers (37,71) found both clay and silt to be in greater amounts within the crust than the soil below. The quantity of clay was only slightly higher in the crust but the silt was considerably higher in the crust. Chepil (16) also reported a high degree of cloddiness from mixtures of 80% silt and 20% clay.

It is well known that manipulation of the soil in any way at high moisture contents cause destruction of the soil physical condition, a condition simulating puddling in the field. Moe *et al.* (47) has obtained modulus of rupture values as high as 13.1 bars from a Montana soil (Pylon) which was stirred when wet to break down the weak natural soil aggregation.

Duley (22) indicated that soil crusts had a greater bulk density, more coarse material, and less organic matter than the underlying soils. Tree (26) measured bulk density of some crusts as 1.39 compared to only 1.19 g/cm^3 for the soil below. Lemos and Lutz (37) found that bulk density of crusts were significantly greater than that of the soil beneath. Crust bulk density averaged 23.5% higher.

It has been a widespread belief that soil crusting decreases the diffusion of air. However, van Bavel (66) concluded that a thin compact surface layer has practically no effect on the process of air diffusion. Investigations by Domby and Kohnke (21) show that, unless the soil surface is completely impervious, or very wet, the rate of air diffusion through the soil does not depend on the properties of this layer.

Strong correlations have shown the kind and level of cations and anions present in the soil plays a major role in crust formation. It is widely known that the ratio of divalent cations to sodium is an important factor in crust formation. Numerous groups (1,2,57,60) have indicated the relationship of exchangeable sodium to modulus of rupture appears to be positive and linear. Allison and More (2) found for two Pachappa loam soils with 14% clay, one with 3% and the other 54% exchangeable sodium, that modulus of rupture values were 1.35 and 3.7 bars, respectively. Lutz and Pinto (38) found that levels of phosphorus (P) had effects on the modulus of rupture. Their data demonstrates P at lower rates of 50 to 100 lbs/acre reduced crust strength, but larger rates increased the hardness of crusts.

There was evidence indicating larger increments of P increased the negative charge of the clay particles to the point that dispersion occurred and resulted in a greater modulus of rupture. This is especially worth noting from both the agronomic and economic standpoint since 50 to 100 lbs per acre of P are feasible rates to apply. The literature presents varying results on crust strength with the addition of potassium. Reeve et al. (57) found that for eight potassium treated soils only three responded with a decreased modulus of rupture. Buehrer (13) indicated clods became more friable and swelled to a lesser extent following a treatment consisting of wetting with KCL solution and drying. Varying results in this respect can be attributed to the type of clay present in the soil. Klages (34) reported that soils of high montmorillonite content usually show poor structural characteristics. Treatment of this clay with KCL and heat converted some montmorillonite to the nonexpanding illite. When this happened, the colloids appeared to be less subject to swelling and shrinking.

Seedling emergence can be correlated to crust strength and is a function of the seedlings vigor. Richards (60) found for a fine sandy loam soil under field conditions, no decrease in emergence of beans with a crust strength of 108 millibars, even though surface crusting effects were markedly in evidence. However, with the exchangeable sodium percentage (ESP) artificially increased to 37, it was found that crust strength increased to 273 millibars, and no bean seedlings emerged. He assumed the failure to obtain a stand was due to the increased mechanical strength of the surface crust caused by the presence of exchangeable sodium. Allison (1) concluded that the critical modulus of rupture for sweet corn on the Pachappa loam soil is between 1.2 and 2.5 bars. Hanks and Thorp (32) found wheat, sorghum, and soybean seedling emergence was a function of soil moisture and modulus of rupture of crusts. It has already been noted that modulus of rupture is a function of moisture. They used moisture regimes consisting of field capacity, one-half and one-fourth of the available water remaining in the soil. In all cases the emergence percentage was greater at higher moisture contents at all crust strengths 0-.8 bars. However, their data indicate that a crust strength of .2 bars can reduce emergence of these seedlings. It is apparent such data on different seedlings could be useful in management.

It is commonly believed that successive cycles of wetting and drying cause structural changes in the soil mass. Lemos and Lutz (37) found a decrease in modulus of rupture with successive cycles of wetting and drying. The decrease was accompanied by a 12% increase in volume of the briquets. Each time the soil was wetted the rapid intake of water caused unequal swelling of the soil mass. The differential swelling, associated with the cementation of the clay particles when the soil mass shrinks by drying, caused planes of weakness which accounted for the lower modulus of rupture. The associated changes in volume of the soil briquets are permanent modifications in internal structure.

Researchers (1,2,41) have been rather successful in decreasing soil strength and improving soil characteristics with the synthetic soil conditioners hexadaconal, VAMA, and HPAN. However, such conditioners are extremely expensive.

The effects of gypsum on soil crusing have been measured by few investigators. Moe _et al_. (47) found that 8 tons per acre gypsum, applied in the laboratory, significantly reduced crust strength of a Montana soil (Pylon) with serious crusting problems. Mixing the subsoil with the topsoil and gypsum was slightly more successful in reducing crust strength. In addition to the standard procedure, a treatment of freezing and thawing was also given to the artificial crust in conjunction with the gypsum and subsoiling treatments. The freeze-thaw method significantly reduced crust strength of all treatments to a greater degree than the standard treatments alone.

Kultgen and Sims (35) measured modulus of rupture decreases from 1.55 bars on check plots to .8, 1.09, and 1.02 bars on field plots that received 2000 and 500 lbs gypsum per acre and 20,000 lbs manure per acre, respectively. These treatments were applied on a nonsodic silt loam soil in Cascade County, Montana.

The literature shows that factors such as moisture content, drying conditions, texture, kind and level of exchangeable cations in the soil, and interactions of these factors significantly influence crust strength. It is apparent that the modulus of rupture technique has been largely confined to laboratory treatments and not applied directly in the measurement of field treatments. Also, the literature has not described how modulus of rupture changes with depth near the soil surface.

METHODS AND MATERIALS

The field selected for the study is located on the Harvey Walters farm in the Yellowstone Valley 12 miles west of Forsyth, Montana. The soil status was saline-alkali and provided only a limited amount of forage grazing.

Experimental Design and Treatments

The experimental area (Figure 1) was laid out in blocks of irrigation treatments (frequency 5, 10 and 15 days). Irrigation treatments were split with three rates of gypsum (0, 5 and 10 tons/acre). Three replications provided a total of 27 plots. Irrigation plots were 60 x 100 feet in size. Gypsum plots were 20 x 100 feet. Ditches between the blocks of irrigation treatment allowed good water control.

Preliminary tests on gypsum requirement of this soil indicated only a few samples exceeded 10 tons/acre and none exceeded 15 tons/acre. This data provided the means for choice of gypsum rates.

Laboratory Determination of Hydraulic Conductivity

Undisturbed soil cores taken in the field from various depths were evaluated for hydraulic properties. A hydraulic soil sampling device fitted with a three inch bit containing a metal sleeve, removed cylindrical soil cores three inches deep. The soil cores contained within the metal sleeve were wrapped in plastic to prevent moisture loss.

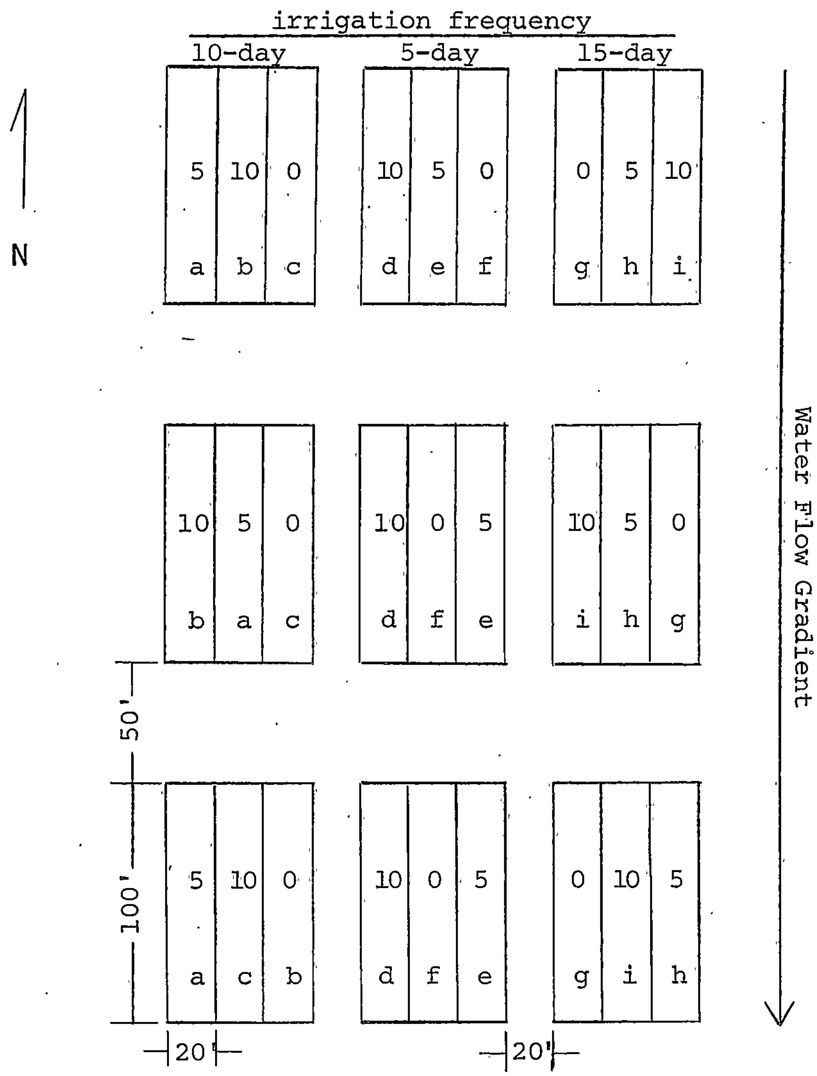


Figure 1. Field plot diagram of gypsum amendment and irrigation frequency study for reclamation of saline and alkali soil. The numbers within the plots designate gypsum rate in tons per acre, while the letters designate plot replication.

Hydraulic conductivities at various soil-water potentials were measured using a modification of Richards (58) procedure as described by Boersma (8). Essentially, the procedure consists of attaching hanging water columns to both ends of the cylinder by way of a porous plate in direct contact with the undisturbed soil core. By adjusting the heights of the hanging water columns various soil-water potentials can be applied to the soil. Hydraulic conductivities were determined at the various soil-water potentials when nearly constant flux occurred. Richards (58) explains that the porous plates cause some impedence to flow so at least two tensiometers are required to estimate the soil-water potential gradient within the sample. However, we assumed that the impedence due to our plates was insignificant and, therefore, simplified the method considerably by measuring the potential gradient directly from the hanging water columns.

The equation used was a modification of the Darcy flow equation

$$K = \frac{Q\Delta L}{tA\Delta H} \qquad [5]$$

where K is the hydraulic conductivity, Q is the volume of water passing through the material in time (t), ΔL is the length of the soil sample, A is the cross sectional area of the soil column, and ΔH is the hydraulic head difference. Water used in the laboratory to measure hydraulic conductivity had the same approximate salt status as that used for irrigation of the field plots. Of the twenty undisturbed soil cores analyzed with irrigation water, ten were given a second treatment with a saturated gypsum solution to observe any difference in the hydraulic properties. These data are presented in a graphical form plotting hydraulic conductivity against soil-water potential.

Parshall Flumes

Two parshall flumes were installed in an attempt to measure the water infiltration for each irrigation treatment. A unique system of irrigation ditches enable one nine-inch parshall flume to feed the three irrigation treatments individually, and at our discretion. The irrigation blocks were border diked so excess runoff water could be contained within the block as long as desired. One six-inch parshall flume with a water level recorder measured the runoff water from each separate irrigation block. This procedure enabled an estimation of both the water put on each irrigation treatment, and the water which ran off, this difference being infiltration.

Tensiometer Systems

Nine mercury manometer tensiometer systems were placed in the north replication of each irrigation and gypsum treatment. Each system consisted of 5 tensiometers at soil depths .5, 1.5, 2.5, 3.5, and 4.5 feet. All tensiometers were constructed of a porous cup glued to a plastic shaft. A five inch pyrex extension on the shaft enabled visual evidence that the tensiometer water level was satisfactory. About thirty feet of small diameter nylon tubing connected each tensiometer of the system to a single mercury source at the base of a meter stick. The long nylon tubing enabled all readings of soil-water matrix potential to be made off the experimental area, a necessity during periods of irrigation.

Soil Water Extraction Tubes

The ability to predict changes in the soil solution concentration in a rapid and comprehensive manner during infiltration and drainage was accomplished as follows. Porous cups glued to plastic access tubes were placed at the same depths as all the tensiometers (.5, 1.5, 2.5, 3.5, 4.5 feet). A vacuum device powered by a portable generator created a suction on the access tubes, thereby, extracting soil solution into the porous cups. The soil solution was immediately removed from the porous cups via a long straw with a bottle trap which captured the extracted soil solution.

Evaluation of the Soil Salt Status

Soil samples were taken before and after treatments (gypsum and irrigation). These samples were taken in the north nine plots at one foot intervals to a depth of five feet. Saturated paste extracts were analyzed for electrical conductivity, sodium, calcium, magnesium, and potassium.

Sodium-adsorption-ratios (SAR) were calculated for all samples by the equation:

$$SAR = \frac{[Na]}{\sqrt{([Ca] + [Mg])/2}} \qquad [6]$$

where the ion concentrations are in millequivalents per liter.

Measurement of Field Soil Hydraulic Properties

A water movement study in the field requires two types of measurements; 1) soil-water content at various depths with time, 2) soil-water potential with depth and time. Such data can be directly or indirectly determined by use of neutron scatter equipment, tensiometers, desorption curves, and laboratory determined hydraulic conductivity values.

The hydraulic conductivity and flux of water in the field were calculated by use of Darcy's Law

$$Q = \frac{\Delta\theta}{t} = KA \cdot \frac{d\Psi}{dx} \quad [7]$$

where K is the hydraulic conductivity (cm/hr), A represents a constant area (1 cm^2), Q is the flux of water (cm^3/hr), $d\Psi$ is the total potential head (cm) equal to the sum of the soil matrix and gravitational potentials, dx is the vertical distance of flow, θ is the soil-water content (cm^3) and t is time (hours). Soil-water content (θ) was measured directly in the field during the drainage period following all irrigation treatments with neutron scatter equipment. However, due to the limited use of this equipment during irrigations, attempts were made to employ desorption curves made from disturbed samples on a pressure membrane apparatus. Soil-water potential (Ψ) data from field tensiometers coupled with the desorption curves provided the means for calculating the changes in soil-water content (θ) with time. However, the lack of soil bulk density data in conjunction with very small changes in soil-water content with time made the error of this technique enormous, therefore, the only data presented on soil-water content change during irrigations is that measured by the neutron scattering equipment.

Modulus or Rupture

Modulus of rupture is a measure of the breaking strength of materials, and is defined as the maximum fiber stress, ie., force per unit area, that a material will withstand without breaking. The effects of field treatments (gypsum and irrigation) upon soil crust strength of the saline-alkali soil was evaluated by means of the modulus of rupture technique as reported by Richards (60), with one modification. The modification consisted of finer soil sieving, 1- versus 2-millimeters. It was reported by Moe et al. (47) that the use of the finer sieve increased modulus of rupture values slightly, but decreased variation due to replication. The equation used was:

$$S = \frac{3\ F\ L}{2\ b\ d^2} \qquad [8]$$

where S is the modulus of rupture in dynes per cm^2, F is the breaking force in dynes (the breaking force in grams weight x 980); L is the distance between the two lower supports of the apparatus (cm), b is the width of the briquet, and d is the depth or thickness of the briquet (cm). The bar is a CGS unit of pressure and is equal to 1,000,000 dynes per cm^2, and is the accepted unit in expressing modulus of rupture for soils.

Essentially, the procedure consisted of gathering the soil samples from various treatments from the field, followed by crushing and sieving, then, in the laboratory, the samples were wetted and dried simulating field swell-shrink forces which promote soil crusts. The force necessary to break the artificial crust was measured with the modulus of rupture apparatus. Samples were taken in replication, before and after irrigation treatments, at three soil depths (0-1, 1-3, 3-6 inches.)

The swell-shrink factor of soil material is a pertinent property and was determined on all soil samples. This was accomplished by measuring the dimensions of the soil sample used for modulus of rupture before and after a wetting-drying cycle. The equation used was:

$$\text{soil shrinkage} = 23.233 \text{ cm}^3 - (L \times W \times H) \qquad [9]$$

where 23.233 cm^3 represents the constant volume of the brass rectangle, and L is the length, W the width, H the height in centimeters of the soil briquet after drying.

One of the difficulties of this procedure was the collection of representative soil samples by treatment from the field. In order to test the genuine effect of gypsum on crusting properties, exact rates of gypsum (0, 5, 10 and 20 tons per acre) were mixed with soil samples taken from field plots where no gypsum was applied. These samples were then evaluated by modulus of rupture measurements.

Tillage Tests

A device for measuring tillage forces and power requirements was developed by the Agricultural Engineering Department of Montana State University and field tested on the gypsum-irrigation treated plots.

The test machine consisted of a four tool bar frame on which any type of tillage tool can be mounted. The tillage tool used was a chisel cultivator with teeth placed one-foot on center. Other tools such as sweeps, shovels and rods could also be evaluated on this machine.

Tillage forces were measured by a strain gauge transducer mounted between the tool bar frame and the three point hitch. The transducer consists of two extended rings. The strain gauges respond to horizontal forces only and were wired in series to sum forces for both rings. Distance was measured with a rolling land wheel and time was measured with a clock mechanism in the recorder. The recorder was powered by a portable generator. All the equipment including the recorder and generator were mounted on the tool bar frame.

Field tests to evaluate the effect of gypsum rates and irrigation frequencies upon power requirements were made in September 1970. Measurements were made using six chisel shanks 12-inches on center operated at a depth of 4-inches at a ground speed of 1.1 miles/hour. The apparatus was pulled through the 100 foot length of each plot

(Figure 1). Data was summarized as the average force for each treatment.

Sequence of Operation

Summer 1969

1. The experimental field was cleared of native vegetation (Inland saltgrass, Western wheat grass, big sage, annual weeds) and leveled for irrigation.

September 1969

1. randomized block design set up
2. aluminum neutron probe access tubes placed in plots
3. soil samples taken for salt status evaluation
4. three-inch undisturbed cores taken for laboratory determination of hydraulic conductivity

March 1970

1. gypsum rates applied by hand

April 1970

1. the area was planted to grass with barley as a companion crop

June 1970

1. system of irrigation ditches were constructed
2. parshall flunes were installed
3. tensiometer systems installed
4. soil-water extracting tubes installed
5. soil samples taken for modulus of rupture

July 1970

1. irrigation treatments started

September 1970

1. irrigation treatments concluded
2. soil samples taken for salt status evaluation
3. soil samples taken for modulus of rupture
4. plow force data collected-tillage tests

RESULTS AND DISCUSSION

Modulus of Rupture - Laboratory Treatment

Prior to evaluating the influence of field treatments on strength of crust formation, tests were made in the laboratory on soil samples from the plots to measure the effect of gypsum and wetting and drying upon crusting properties of the soil. The modulus of rupture technique measures the force necessary to break a soil crust. Such a technique provided a means for evaluation of treatments upon physical properties of soils and specifically upon the strength of the soil crusts.

Table 1 shows modulus of rupture data obtained on soil from the plot area (0-1 inch depth), which contained known rates of gypsum applied in the laboratory. The laboratory technique requires the addition of water to the soil mixture, thereby, simulating field treatments of gypsum and irrigation. Analysis of variance and the multiple range test gave these results:

1) all gypsum rates decreased crust strength significantly.
2) the 20 ton per acre rate decreased crust strength significantly more than the 5 ton per acre rate.
3) no significant difference between the 10 and 20 ton rates.
4) no significant difference between the 5 and 10 ton rates.

Table 2 shows modulus of rupture data obtained from a field soil (0-1 inch depth) at a second location within the experimental area.

Table 1. Data table, analysis of variance and multiple range test on modulus of rupture values for the saline and alkali soil (0-1 inches). Given rates of gypsum were added in the laboratory.

Data Table

replication	0 T/A	5 T/A	10 T/A	20 T/A
	bars			
1	8.163	3.667	3.439	2.874
2	7.772	3.121	2.968	2.874
3	7.594	3.857	3.113	3.066
4	7.057	3.482	3.664	3.741
5	7.206	3.939	4.029	3.055
6	7.065	3.260	3.243	3.752
mean	7.476	3.554	3.409	3.227

Analysis Of Variance

variation due to	df	SS	mean square	s	F-value
replication	5	.403	.0806		.4444 NS
gypsum	3	75.200	25.0670		138.1 **
error	15	2.723	.1815	.426	
total	23	78.326			

Multiple Range Test

force mean number	1	2	3	4
gypsum rate	0	5	10	20
mean S 1/ value	7.476	3.554	3.409	3.227

1/ The S-value represents modulus of rupture in bars
NS Not significant
** Significant differences between treatments p = .01
__ Underlined means are not significantly different

Table 2. Data table, analysis of variance and multiple range test on modulus of rupture values for the saline and alkali soil (0-1 inches). Given rates of gypsum were added in the laboratory.

Data Table

replication	0 T/A	5 T/A	10 T/A	20 T/A
	bars			
1	3.722	3.210	2.396	2.306
2	3.836	2.460	2.241	2.210
3	4.434	2.604	2.251	2.102
4	3.953	2.356	2.441	2.682
5	4.080	2.534	2.272	2.139
6	4.124	2.212	2.263	2.257
mean	4.026	2.563	2.311	2.283

Analysis of Variance

variation due to	df	SS	mean square	s	F-value
replication	5	.198	.03960		.6136 NS
gypsum	3	12.388	4.12900		63.98 **
error	15	.968	.06453	.8034	
total	23	13.554			

Multiple Range Test

force mean number	1	2	3	4
gypsum rate	0	5	10	20
mean S[1/] value	4.026	2.563	2.311	2.283

1/ The S-value represents modulus of rupture values in bars
NS Not significant
** Significant difference between treatments p = .01
___ Underline means are not significantly different

The same laboratory treatments (gypsum plus water) gave these results:

1) all gypsum rates decreased crust strength significantly,
2) both the 10 and 20 ton per acre rates decreased crust strength significantly greater than the 5 ton per acre rate.
3) no significant difference between the 10 and 20 ton per acre rates.

These data point out the large differences in soil properties between locations in the field.

Gypsum was very effective in modifying soil physical properties and thus reducing crust strength of this alkali soil. However, researchers (1,32,60) indicate successful seedling emergence of most crops require a modulus of rupture value less than one bar. Using this as a criterion it is apparant the laboratory treatment of gypsum and one wetting-drying cycle was not sufficient (see Tables 1 and 2) in lowering the crust strength to acceptable values of less than one bar. Since it is impossible to exactly duplicate field conditions in the laboratory, these data can only be interpreted to indicate that gypsum may be an effective treatment influencing the physical properties of this soil.

Modulus of Rupture - Field Treatments

Table 3 shows modulus of rupture values of soil samples taken at three depths in replication over all treatments. The data represents a gypsum effect only, since no irrigation treatments had been applied.

Table 3. Modulus of rupture values (bars) as a function of field gypsum treatments, depth, and irrigation frequency location (no irrigation water applied at this time).

gypsum rate T/A	depth in inches	5-day frequency location	10-day frequency location	15-day frequency location
0	0-1	8.575	7.993	8.880
0	0-1	9.211	8.548	7.574
0	1-3	10.022	9.662	8.137
0	1-3	9.198	9.040	9.052
0	3-6	10.212	10.739	11.403
0	3-6	11.496	12.004	10.111
5	0-1	8.010	7.177	5.355
5	0-1	7.236	7.819	8.109
5	1-3	7.924	7.903	4.882
5	1-3	9.250	6.116	8.650
5	3-6	10.033	11.968	10.440
5	3-6	11.545	11.357	9.200
10	0-1	7.429	4.303	5.218
10	0-1	5.997	6.871	7.343
10	1-3	9.066	7.872	8.055
10	1-3	7.962	9.205	8.905
10	3-6	10.432	9.337	11.433
10	3-6	10.011	11.707	10.098

Table 4a shows the analysis of variance and multiple range test on modulus of rupture data with gypsum but prior to irrigation treatments (data Table 3). A significant effect due to depths was found. The accompanying multiple range test on depths indicates modulus of rupture increased with depth to a tested six inches and that each depth was significantly different from each other. Such an effect with depth can be attributed to two factors; 1) the gypsum application, and 2) the particle size change with depth.

The analysis of variance, Table 4a, indicated no significant difference due to gypsum alone, however, there was a significant gypsum x depth interaction. Table 4b shows further analysis of the gypsum x depth interaction. Here, case 2 indicates 10 T/A gypsum did significantly reduce the crust strength of the 0-1 inch soil mass but not the 1-3 or 3-6 inch zones. It follows that gypsum alone was not significant because that particular test was made over all depths. The lower depths 1-3 and 3-6 inches, masked out the significant effect of gypsum within the 0-1 inch zone. Case 1 of Table 4b indicates crust strength was reduced by 5 T/A gypsum to a significant degree at the 1-3 depth and to a near significant degree at the 0-1 inch depth. Again the effects of the surface applied gypsum were not present at the 3-6 inch depth. This analysis of the gypsum x depth interaction implies the gypsum, which was applied to the surface and disked in, did decrease crust strength in the upper portion of the

Table 4a. Analysis of variance on modulus of rupture data collected prior to irrigation treatments (Table 3). Included is the multiple range test on depth.

Analysis of Variance

variation due to	df	SS	mean square	s	F-value
replication	1	2.305	2.305		4.45 NS
irrigation areas	2	3.292	1.646		3.18 NS
error a	2	1.035	.518		
sub total A	5	6.632			
gypsum	2	14.528	7.264		2.35 NS
gyp x irr	4	3.173	.793		.26 NS
error b	6	18.539	3.090		
sub total B	17	36.240			
depth	2	111.417	55.708		222.8 **
error c	2	.500	.250	.5	
sub total C	5	114.222			
depth x irr	4	2.967	.742		.70 NS
depth x gyp	4	10.800	2.700		2.55 #
depth x gyp x irr	8	2.504	.313		.30 NS
error d	16	16.946			
Total	53	181.374			

NS Not significant
** Significant difference between treatments p = .01
# Significant difference between treatments p = .1

Multiple Range Test On Depth

depth mean number	1	2	3
depth in inches	3-6	1-3	0-1
mean S@ value	10.751	8.383	7.314
	all depths significantly different from each other		

S@ The S-value represents modulus of rupture in bars

Table 4b. Analysis of significant gypsum x depth interaction from Table 4. Statistical technique used is described in Steel and Torrie page 208.

Data Table

depth in inches	Gypsum Rate (T/A) 0	5	10
0-1	50.781	43.706	37.161
1-3	55.111	44.724	51.065
3-6	65.965	65.543	63.018

Case 1. Comparison of 0- and 5-T/A gypsum at all depths

depth in inches	Gypsum Rate (T/A) 0		5	F-value
0-1	50.781	vs.	43.706	2.32 NS
1-3	55.111	vs.	44.724	4.99 *
3-6	65.965	vs.	64.543	.09 NS

Case 2. Comparison of 0- and 10-T/A gypsum at all depths

depth in inches	Gypsum Rate (T/A) 0		10	F-value
0-1	50.781	vs.	37.161	8.58 **
1-3	55.111	vs.	51.065	.76 NS
3-6	65.965	vs.	63.018	.40 NS

Case 3. Comparison of 5- and 10-T/A gypsum at all depths.

depth in inches	Gypsum Rate (T/A) 5		10	F-value
0-1	43.706	vs.	37.161	1.98 NS
1-3	44.724	vs.	51.065	1.86 NS
3-6	64.543	vs.	63.018	.01 NS

NS Not significant
* Significant differences between treatments $p = .05$
** Significant differences between treatments $p = .01$

profile but, where no gypsum was directly applied, 3-6 inches, the measured modulus of rupture was significantly higher. Case 3 of Table 4b indicates there was no significant difference between the 5- and 10-T/A gypsum rates in decreasing crust strength at the various depths.

Second, the actual surface crust as observed in the field varied from 1-3 inches in thickness, and was dominated by the silt fraction whereas the soil below the crust, 3-5 inches, was a clay type texture. Such a textural arrangement on crusted soils has been observed by other investigators (37,71). Researchers (15,16, 64) have concluded that the greater the clay content the greater the modulus of rupture. It follows, then, that the soil directly beneath the surface crust, which was dominated by clay, would have a greater "ability" to form a hard crust upon drying then the silt dominated surface. This was the result upon oven drying of samples for the modulus or rupture procedure, that is, an increase in modulus or rupture with depth. At first glance the data appeared to contradict the field observation and concept that a hard surface crust, the top 1-3 inches, was the zone limiting seedling emergence since the lower depth (3-6 inches) had a greater modulus of rupture. However, this was not the real case in the field. At no time during the hot summer did the soil dry out below an average depth of one inch. This meant a hard crust formed only at the very surface, thereby limiting plant emergence.

The soil immediately below the dry crust, which was high in clay content and had a greater "ability" to form a hard crust upon drying, remained moist through the summer and presented no great barrier to seedling emergence.

Table 5 shows modulus of rupture of soil from three depths obtained after the completion of all irrigation treatments over the gypsum rates. Analysis of variance of these data, Table 6, indicates a highly significant effect due to depths. The multiple range test (Table 7) showed significant differences between all depths and can be attributed to the same two factors as previously discussed; 1) the gypsum application, and 2) the particle size change with depth.

Table 6 also indicates a highly significant effect due to gypsum. The multiple range test on gypsum rates, Table 7, indicates significant differences between all rates (0, 5 and 10 tons per acre).

Table 6 also indicates a significant effect due to irrigation treatments at the .1 significance level. Figure 2 demonstrates this strong effect of irrigation upon soil crust strength. Although the multiple range test indicated irrigation frequencies did not affect crust strength, these data in Table 8 which are plotted in Figure 3, indicate a real influence of irrigation frequency upon crust strength. Soil crust strength was decreased with more frequent irrigation applications and increasing rates of gypsum. An interesting relationship exists on plots with no gypsum. As can be seen in Figure 3, at <u>0</u> tons

Table 5. Modulus of rupture values (bars) as a function of field gypsum treatments, depth, and irrigation frequency.

gypsum rate T/A	depth in inches	5-day frequency location	10-day frequency location	15-day frequency location
0	0-1	8.412	7.495	7.106
0	0-1	8.011	7.486	6.886
0	1-3	8.392	8.889	7.435
0	1-3	8.746	8.649	7.864
0	3-6	9.200	9.779	8.458
0	3-6	9.343	9.253	9.203
5	0-1	3.551	4.982	5.121
5	0-1	3.219	3.593	4.998
5	1-3	5.439	6.400	6.943
5	1-3	4.294	7.113	7.447
5	3-6	7.553	9.202	9.103
5	3-6	8.446	8.943	8.933
10	0-1	1.219	2.101	2.589
10	0-1	1.450	1.903	3.045
10	1-3	2.780	3.287	5.443
10	1-3	2.677	3.592	5.832
10	3-6	4.122	6.422	6.241
10	3-6	5.303	5.933	7.130

Table 6. Analysis of variance on modulus of rupture data collected after all irrigation treatments (Table 5). The following table (7) contains the multiple range tests on significant results of this table.

variation due to	df	SS	mean square	s	F-value
replication	1	.049	.049		.1402 NS
irrigation	2	9.244	4.622		13.22 #
error a	2	.699	.3495	1.8697	
sub total A	5	9.992			
gypsum	2	176.507	88.253		50.30 **
gyp x irr	4	16.217	4.054		2.31 NS
error b	6	10.523	1.754	1.3245	
sub total B	17	203.247			
depths	2	98.076	49.038		107.3 **
error c	2	.576	.288	.1700	
sub total C	5	98.701			
depth x irr	4	1.608	.402		2.25 NS
depth x gyp	4	13.091	.327		1.83 NS
depth x gyp x irr	8	2.355	.294		1.64 NS
error d	16	2.871	.179		
Total	53	321.824			

NS Not significant
** Significant difference between treatments p = .01
# Significant difference between treatments p = .1

Table 7. Multiple range test on gypsum rates and soil dpeth which were found significant in the analysis of variance (Table 6) of modulus of rupture data after irrigation treatments.

Treatment mean number	1	2	3
Gypsum rate	0	5	10
Mean S@ value	8.367	6.404	3.948
	all rates significantly different from each other		
Depth mean number	1	2	3
Depth in inches	3-6	1-3	0-1
Mean S@ value	7.920	6.179	4.620
	All depths significantly different from each other		

S@ The S-value represents modulus of rupture in bars.

per acre gypsum, the plots which had the most wetting-drying cycles, 5-day frequency, had the highest crust strength, and the plots with the fewest irrigations, 15 day frequency, had the lowest crust strength. This is the reverse from plots with gypsum treatments. Gerard (28) accounts for this when he found crust strength increases 1) with slow drying, and 2) with increasing exchangeable sodium percentage(ESP). First, Gerard established that slow drying increased the hardness of soil crusts due to the better distribution and orientation of soil particles, especially the silt and clay particles. Therefore, slow drying causes greater close packing of soil particles which enhances crust formation. The saline and alkali conditions of the experimental site rendered the surface soil drying properties very slow. It follows, then that the plots receiving the most irrigation cycles

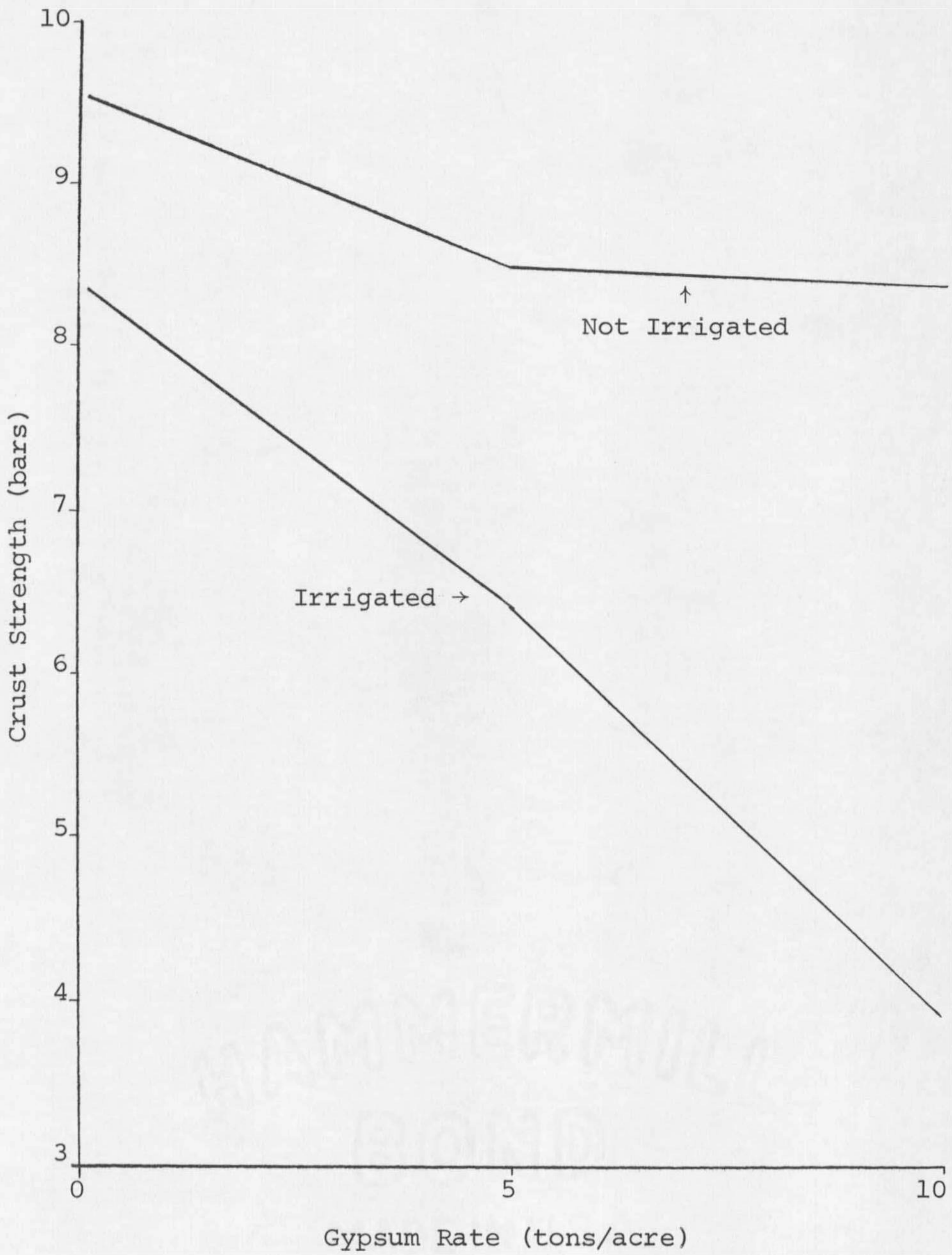


Figure 2. The effect of irrigation and gypsum levels upon soil crust strength.

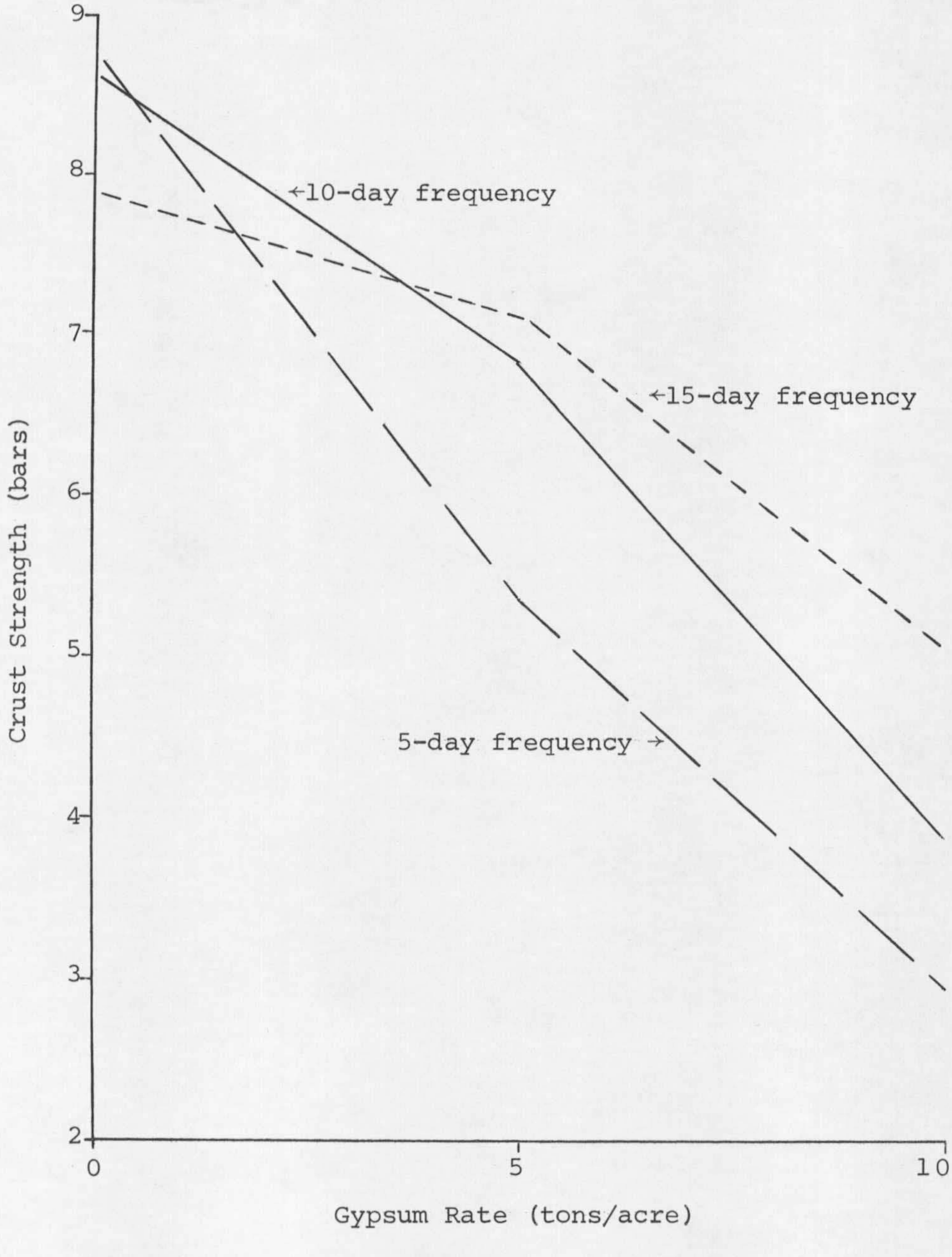


Figure 3. The effect of irrigation frequency at various gypsum levels on soil crust strength.

Table 8. The effect of irrigation frequency with gypsum rates upon modulus or rupture

	Not Irrigated + Gypsum		
Non-irrigated location	0 ton	5 ton	10 ton
5 day	9.786	9.664	9.193
10 day	8.999	8.723	7.772
15 day	8.483	8.216	8.509
	Irrigated + Gypsum		
Irrigation interval	0 ton	5 ton	10 ton
5 day	8.684	5.417	2.924
10 day	8.592	6.706	3.873
15 day	7.825	7.091	5.047

(5-day interval) would be subject to the adverse slow drying effects the most, and consequently a harder crust developed. Second, Gerard stated crust strength increased with increasing ESP. It follows that as more water was applied to the soil and salts were leached out the ESP increased and a harder crust developed.

Thus, 1) gypsum decreased crust strength significantly, and 2) irrigation decreased crust strength. These results held to a depth of six inches but at a decreasing rate as indicated by Table 9 and Figure 4. As can be seen in Figure 4, crust strength was at a maximum on plots without gypsum both before and after irrigation treatments. Also, plots without gypsum had their crust strength decreased a small degree by irrigation alone at all depths. This can be attributed to the leaching out of salts, particularily sodium, from the crusting zone, thereby, reducing the swell-shrink factor which corresponds to a less hard soil crust. Subsequent soil chemical analysis indicated the sodium-adsorption-ratio was decreased by

Table 9. The effect of gypsum and irrigation with depth on modulus of rupture.

Before irrigation	After irrigation
0 ton/acre gypsum	0 ton/acre gypsum
0-1 = 8.464	0-1 = 7.566
1-3 = 9.185	1-3 = 8.329
3-6 = 10.994	3-6 = 9.209
5 ton/acre gypsum	5 ton/acre gypsum
0-1 = 7.284	0-1 = 4.244
1-3 = 7.454	1-3 = 6.273
3-6 = 10.757	3-6 = 8.697
10 ton/acre gypsum	10 ton/acre gypsum
0-1 = 6.194	0-1 = 2.051
1-3 = 8.511	1-3 = 3.935
3-6 = 10.503	3-6 = 5.857

irrigation alone.

Research (1,32,60) has indicated successful seedling emergence of most crops requires a modulus of rapture value less than one bar. Using this as the criterion, and looking at Table 5, it is apparent the 0-1 inch soil layer had its modulus of rupture lowered by 10 tons per acre and a 5-day irrigation frequency to the extent that hardy seedlings could emerge successfully. As previously discussed, it must be remembered that due to the high moisture present in the field below the actual surface crust, below about one-inch, seedlings had no difficulty in emergence till they confronted the dried-out surface crust. Therefore, the higher modulus of rupture values listed in Table 5 for depths 1-3 inch and 3-6 inches are only present for comparing effects

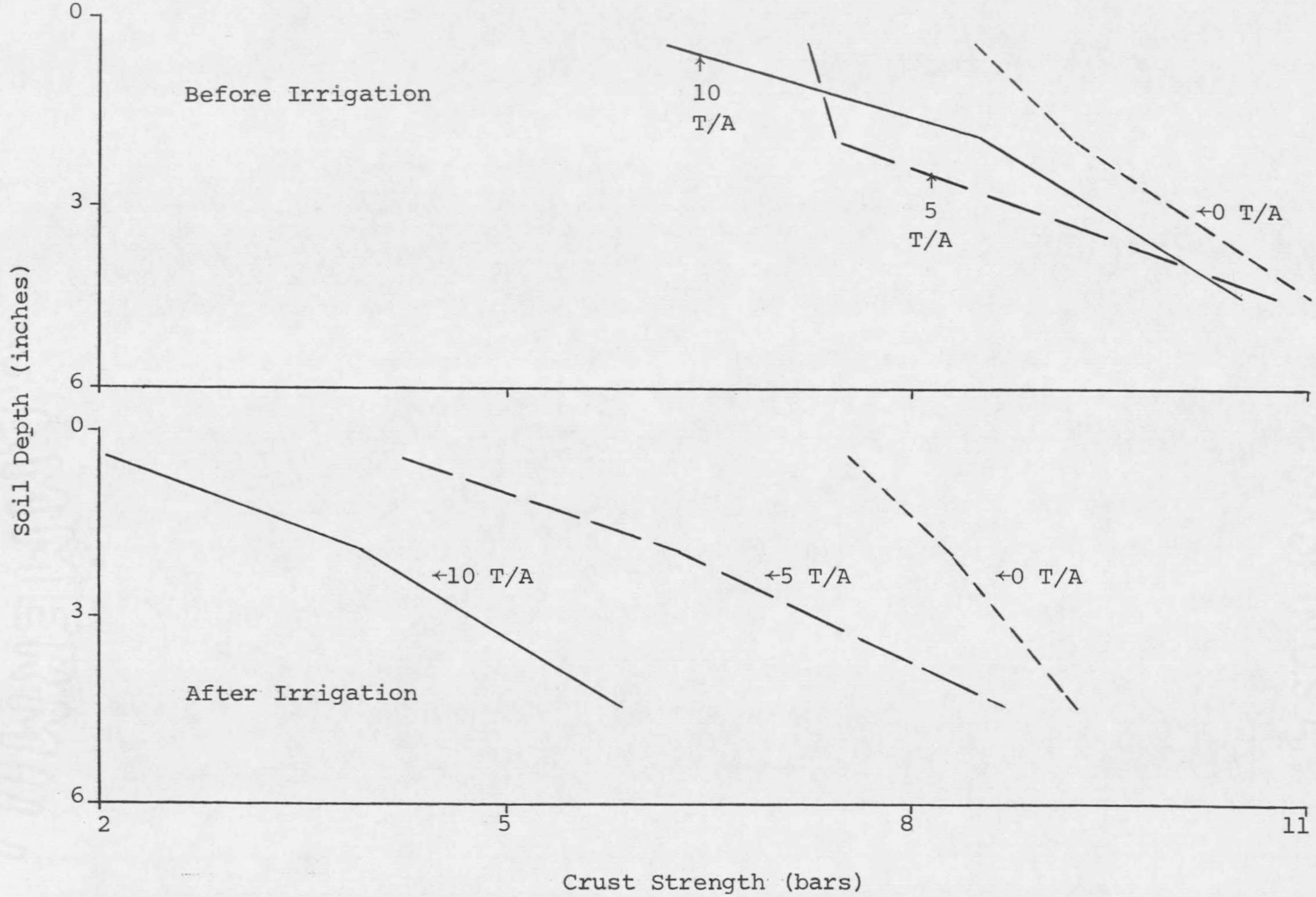


Figure 4. The effect of gypsum levels and irrigation on crust strength at three soil depths.

of treatments and do not represent the genuine soil hardness existing in the field which the seedling had to penetrate. These data do indicate a modification in the soil physical properties.

Soil Swelling and Shrinking

The magnitude of the swell-shrink factor in alkali soils is an important property. Alkali soils swell greatly upon being wetted, thereby, retarding water infiltration, then shrink down to a hard soil crust upon drying, rendering tillage difficult and seedling emergence doubtful.

The effects of gypsum and irrigation treatments on soil shrinkage was evaluated by the Equation 9:

$$\text{soil shrinkage} = 23.233 \text{ cm}^3 - (LxWxH) \quad [9]$$

where 23.233 cm^3 represents the constant soil volume of a briquet form and L is the length, W the width, H the height in centimeters of the soil briquet after drying. Tables 10 and 11 present shrinking factors of soil samples with gypsum treatments before and after irrigation, respectively. Analysis of variance on both sets of data indicated no significant effect due to treatments, however, interesting trends do exist within the data.

Some of these trends are presented in Table 12 and the corresponding Figure 5. Figure 5 (top) depicts the field situation before irrigation, and demonstrates the effect of gypsum on soil shrinkage as a function of depth. As can be seen, soil shrinkage increases with

Table 10. The effect of gypsum before irrigation upon soil shrinkage. The values represent shrinkage due to drying in cm^3 from a original wet volume of 23.233 cm^3.

gypsum rate T/A	depth in inches	5-day frequency location	10-day frequency location	15-day frequency location
0	0-1	7.103	5.514	6.366
0	0-1	5.762	6.891	6.344
0	1-3	6.472	6.896	6.572
0	1-3	6.215	7.375	5.528
0	3-6	6.636	7.611	7.255
0	3-6	8.430	5.908	5.379
5	0-1	6.114	5.993	5.910
5	0-1	5.036	6.991	5.266
5	1-3	6.638	6.742	6.229
5	1-3	5.558	7.485	5.673
5	3-6	6.588	8.225	6.142
5	3-6	6.003	7.902	7.277
10	0-1	5.540	7.126	7.525
10	0-1	5.368	6.035	5.595
10	1-3	6.232	7.584	6.334
10	1-3	7.741	6.901	6.130
10	3-6	6.779	5.608	7.382
10	3-6	8.421	7.472	7.294

Table 11. The effect of gypsum and irrigation upon soil shrinkage. The values represent shrinkage due to drying in cm^3 from an original wet volume of 23.233 cm^3.

gypsum rate T/A	depth in inches	5-day frequency irrigation	10-day frequency irrigation	15-day frequency irrigation
0	0-1	5.546	5.015	7.624
0	0-1	6.604	6.104	6.344
0	1-3	6.017	6.293	7.217
0	1-3	7.140	6.562	6.528
0	3-6	5.933	5.996	6.549
0	3-6	7.723	6.301	6.379
5	0-1	5.145	5.427	5.453
5	0-1	5.247	6.123	5.266
5	1-3	4.893	4.756	5.915
5	1-3	5.220	5.895	5.673
5	3-6	6.150	7.144	5.297
5	3-6	6.409	6.335	7.277
10	0-1	6.785	5.584	6.734
10	0-1	4.680	4.737	5.294
10	1-3	6.362	5.470	6.502
10	1-3	5.082	5.841	6.435
10	3-6	5.993	7.375	6.588
10	3-6	6.439	6.937	7.025

depth which can be attributed to the inherent soil particle size distribution and surface applied treatments. The 0-1 inch depth was

Table 12. The effect of gypsum and irrigation upon soil shrinkage at various soil depths. The values represent shrinkage due to drying in cm^3 from an original wet volume of 23.233 cm^3.

depth in inches	Gypsum rate T/A	Soil shrinkage (cm^3) before irrigation	Soil shrinkage (cm^3) after irrigation
0-1	0	6.330	6.206
0-1	5	5.885	5.443
0-1	10	6.215	5.636
1-3	0	6.510	6.626
1-3	5	6.387	5.392
1-3	10	6.820	5.949
3-6	0	6.870	6.480
3-6	10	7.159	6.726

dominated by silt whereas the soil below increased in clay with depth. A greater swell-shrink factor can be expected with increasing clay content. The effect of the surface applied gypsum was most apparent in the 0-1 inch depth; no noticeable effect was present at the 3-6 inch depth where shrinkage actually increased with gypsum treatments. It is difficult to explain why the 5 ton per acre gypsum rate decreased soil shrinkage more than the 10 ton rate in Figure 5. However, the error in collecting a representative gypsum treated sample from the field could account for this inconsistency. Figure 5 (bottom) represents the same plots as Figure 5 (top) but soil samples were taken after irrigation treatments. Irrigation did reduce soil shrinkage on

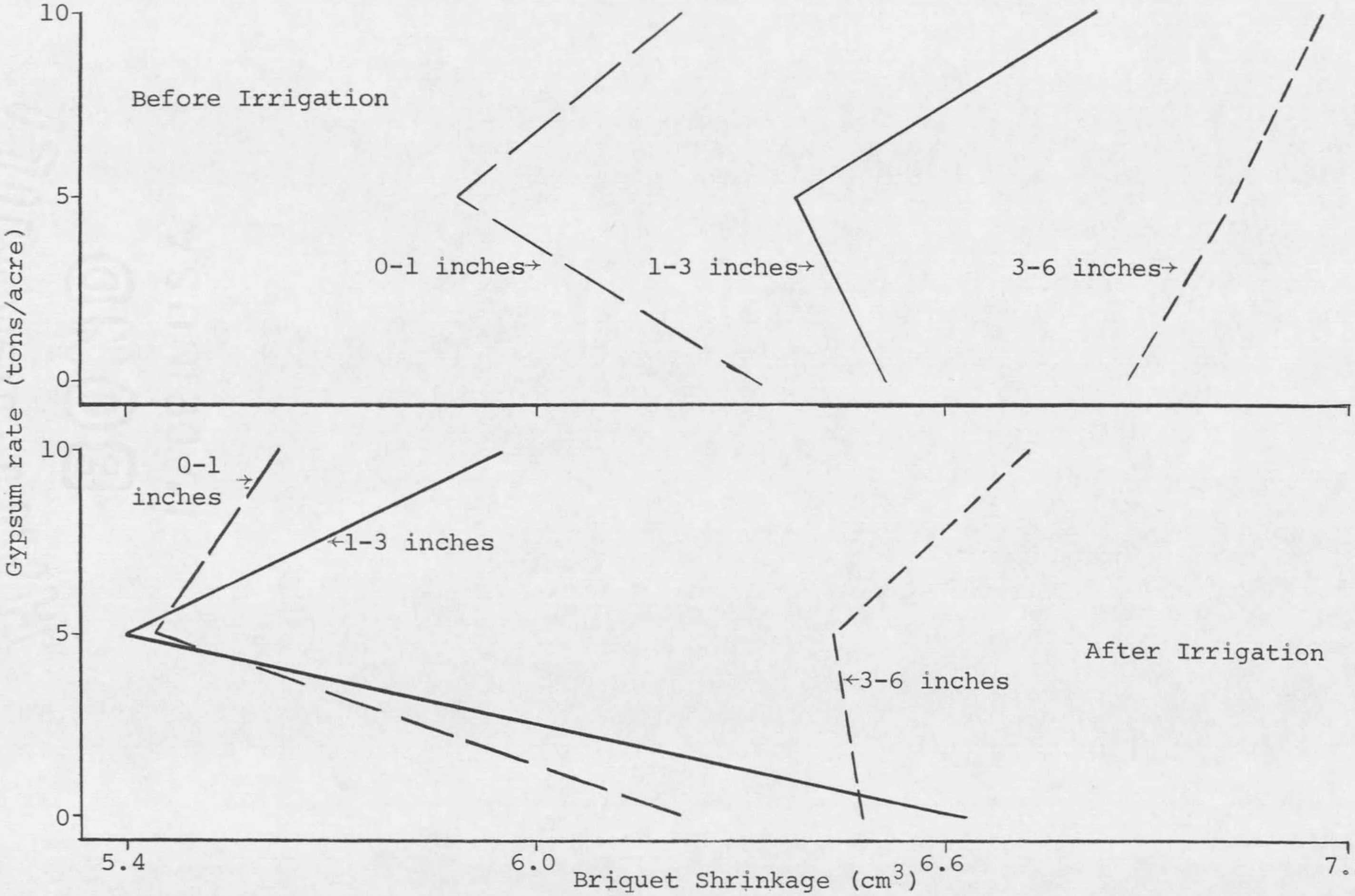


Figure 5. The effect of gypsum and irrigation upon soil shrinkage at various soil depths. The values represent shrinkage due to drying in cm^3 from an original wet volume of 23.233 cm^3.

plots without gypsum which can be attributed to the leaching out of salts, particularily sodium, and subsequent decreases in sodium-adsorption-ratio (SAR). However, the magnitude of the reduction in soil shrinkage was much greater with gypsum treatments because the calcium from gypsum replaced sodium in the soil system thereby reducing the SAR.

The effect of irrigation frequency on soil shrinkage is demonstrated in Table 13 and Figure 6. These data indicate frequent

Table 13. Soil shrinkage as a function of gypsum rates and irrigation frequency. The values represent soil shrinkage due to drying in cm^3 from an original wet volume of 23.233 cm^3.

Gypsum rate	Irrigation Frequency		
T/A	5-days	10-days	15-days
0	6.494	6.045	6.774
5	5.511	5.947	5.814
10	5.890	5.991	6.430

wetting-drying cycles coupled with gypsum treatments was most effective in reducing soil shrinkage. Frequent irrigations resulted in more gypsum becoming soluble and more sodium being replaced by calcium on the clay system; thus upon drying a better physical condition resulted.

Tillage Tests

A device for measuring tillage forces and power requirements was field tested on the gypsum-irrigation treated plots. The objective was to determine if gypsum decreased the power required to pull a plow tool through the soil. Such an effect would mean less wear and tear on machinery and less fuel consumption when plowing a field, consequently, an increased profit per acre of land.

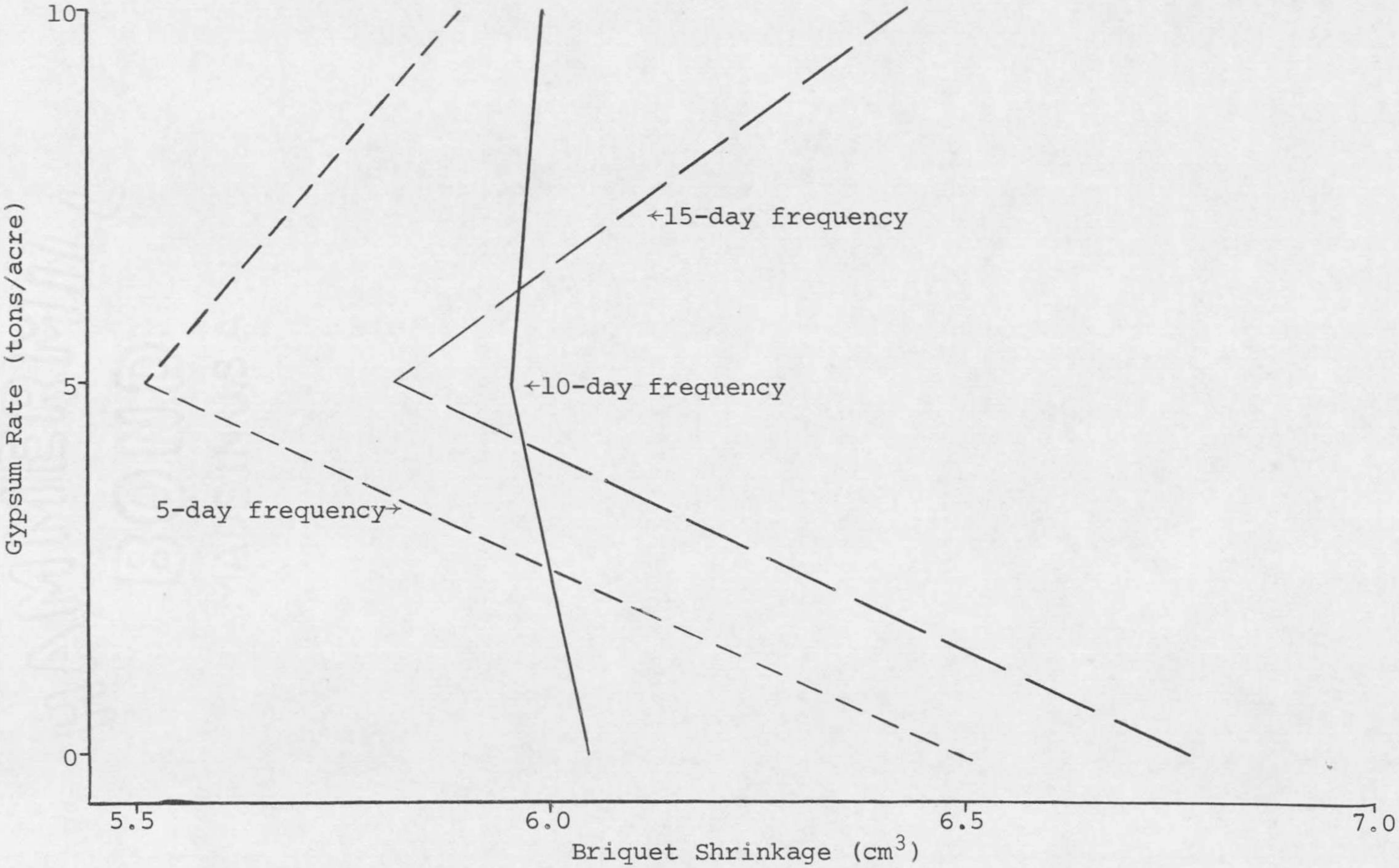


Figure 6. The effect of irrigation frequency and gypsum levels on soil shrinkage. The values represent soil shrinkage due to drying in cm^3 from an original volume of 23.233 cm^3.

Analysis of variance indicated no significant differences were present due to treatments, however, significant variation due to replication was present. Therefore, field variation masked out treatment variations.

The field variation was attributed to two factors. First, as has been pointed out, there was considerable soil variation in the plot area. Second, there was considerable variation in the amount of vegetation in different parts of the field. Some parts of the field had almost no vegetation where as other areas were completely dominated by a thick growth of kochia weed. It is believed that the added force needed to shear the heavy roots of the kochia weed masked out treatment differences. Also, associated with the magnitude of vegetative growth was soil moisture variation due to plant transpiration, and soil shear strength is largely a function of moisture; the less the moisture the greater the soil shear strength.

A repeat of these tests are planned for the spring of 1971. At this time of the year vegetative and moisture variation will be at a minimum. Also, the number of replications will be increased.

Infiltration Rates

Success in reclaiming saline-alkali soils is governed by the ability of the soil to transmit water. This was demonstrated when Pair and Lewis (55) found a positive correlation between salt removal of the soil profile and water intake rate at the surface. Upon irrigation the alkali condition of the surface soil causes extreme swelling of the soil mass leading to closure of the water transmitting pores. The results of the previous section indicates gypsum and irrigation was effective in reducing swelling and shrinking of alkali soils.

The results of this section demonstrate that the water transmitting properties of the surface soil were increased with gypsum and irrigation treatments. Not only was the infiltration rate increased but the quantity of water moving through the soil was increased. The time required for irrigation water to penetrate to a six inch soil depth was measured with tensiometers. Figure 7 represents three irrigations each 15-days apart and has soil-water matrix potential plotted against time in minutes with gypsum treatments as parameters. In irrigation one, the descending slope of the line for 10 tons per acre gypsum means irrigation water reached the six-inch soil depth sooner than in the case of either the 5- or 0-tons per acre gypsum treatments, consequently a corresponding greater decrease in soil-water matrix potential was measured. The plot without gypsum had no immediate change in soil-water potential indicating water did not reach the six-inch soil depth which can be attributed to the large swelling and subsequent closure of the surface pores. The result, then, was that gypsum increased the water transmitting properties of the surface six-inches.

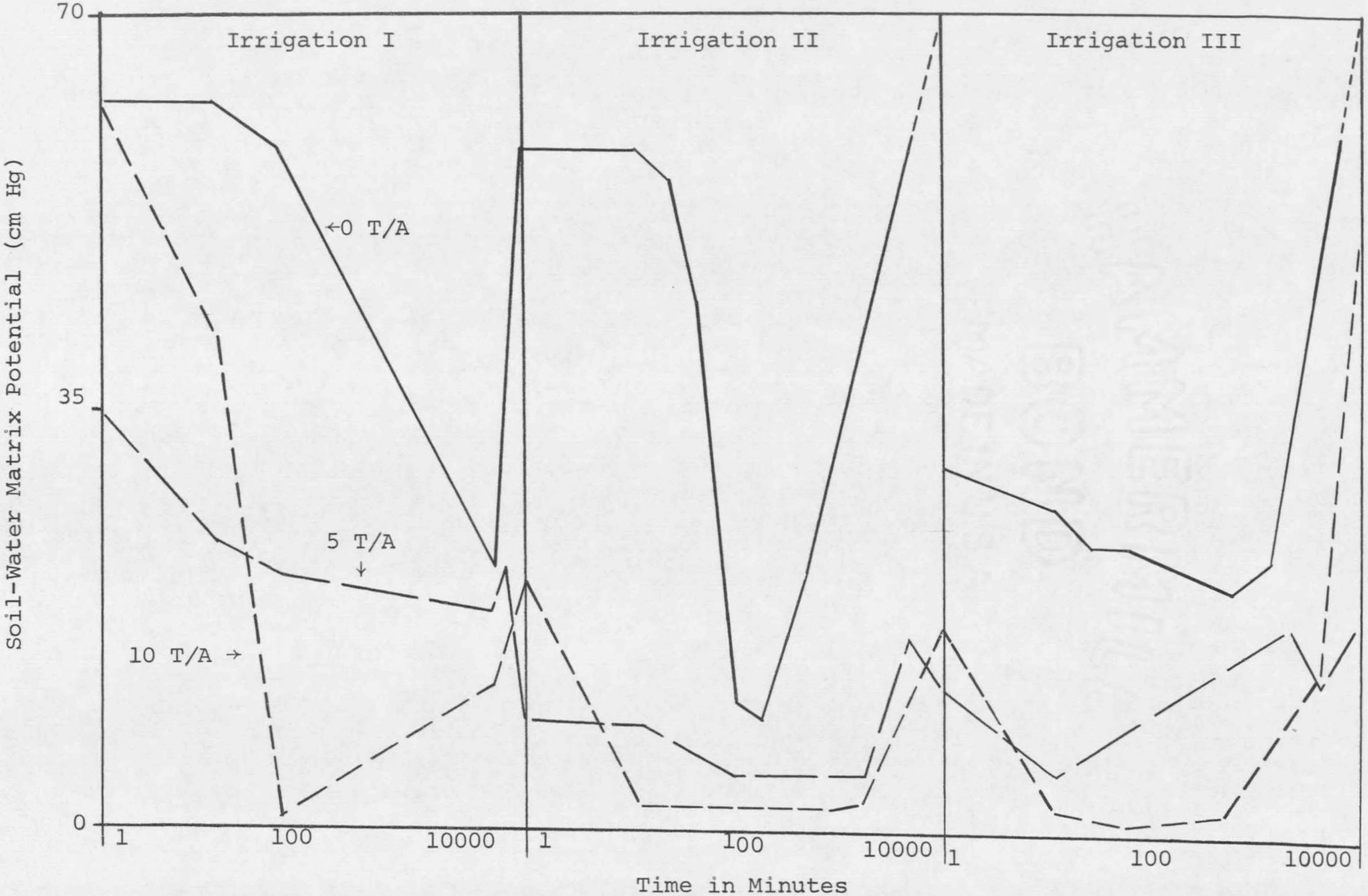


Figure 7. Semi-log plots of soil-water potential at six inch depths during and after 15-day irrigation frequencies as influenced by gypsum rates. Relative infiltration rates can be deduced from the change in tensiometer readings after start of irrigation.

Also in Figure 7, it can be seen that the soil-water matrix potential (Ψ) fell to lower values with increasing rates of gypsum. The lower the matrix potential the greater the quantity of water present at that soil depth. So gypsum not only increased the ability of the soil to transmit water but a greater quantity of water was measured moving through the six inch soil mass.

Figure 8ab and 9abc present similar data as Figure 7. Figures 8a and b denote the four irrigations applied with a 10-day frequency. Figures 9a, b and c denote the seven irrigations applied with a 5-day frequency. The 5-ton per acre gypsum rate is missing from these last three figures due to instrumentation problems. All soil-water matrix potential data, irrespective of irrigation frequency, consistently show gypsum increased the infiltration rate of the surface soil. These figures indicate the 10 ton rate of gypsum was more effective than the 5-ton rate in increasing infiltration, although this did not hold true in every case.

The purpose of gypsum as a soil amendment on saline-alkali soils is to speed up reclamation. This section clearly demonstrated that gypsum increased the quantity of water moving through the surface soil; thus leaching of salts should have been increased.

<u>Hydraulic Conductivity and Water Flux Measurements on Undisturbed Soil Cores in the Laboratory</u>

Hydraulic properties were determined on 20 undisturbed soil cores

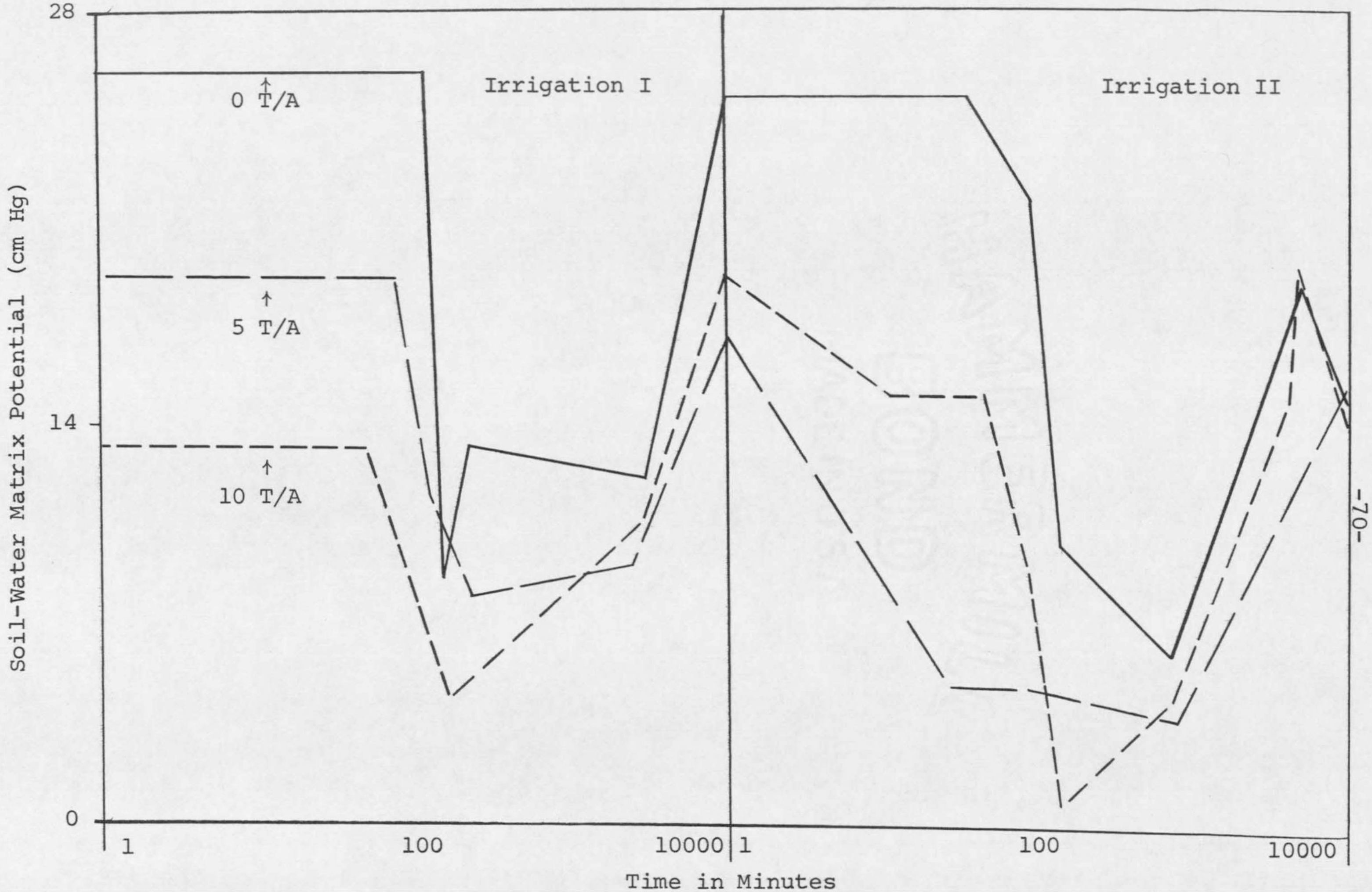


Figure 8a. Semi-log plots of soil-water potential at six inch depths during and after 10-day irrigation frequencies as influenced by gypsum rates. Relative infiltration rates can be deduced from the change in tensiometer readings after start of irrigation.

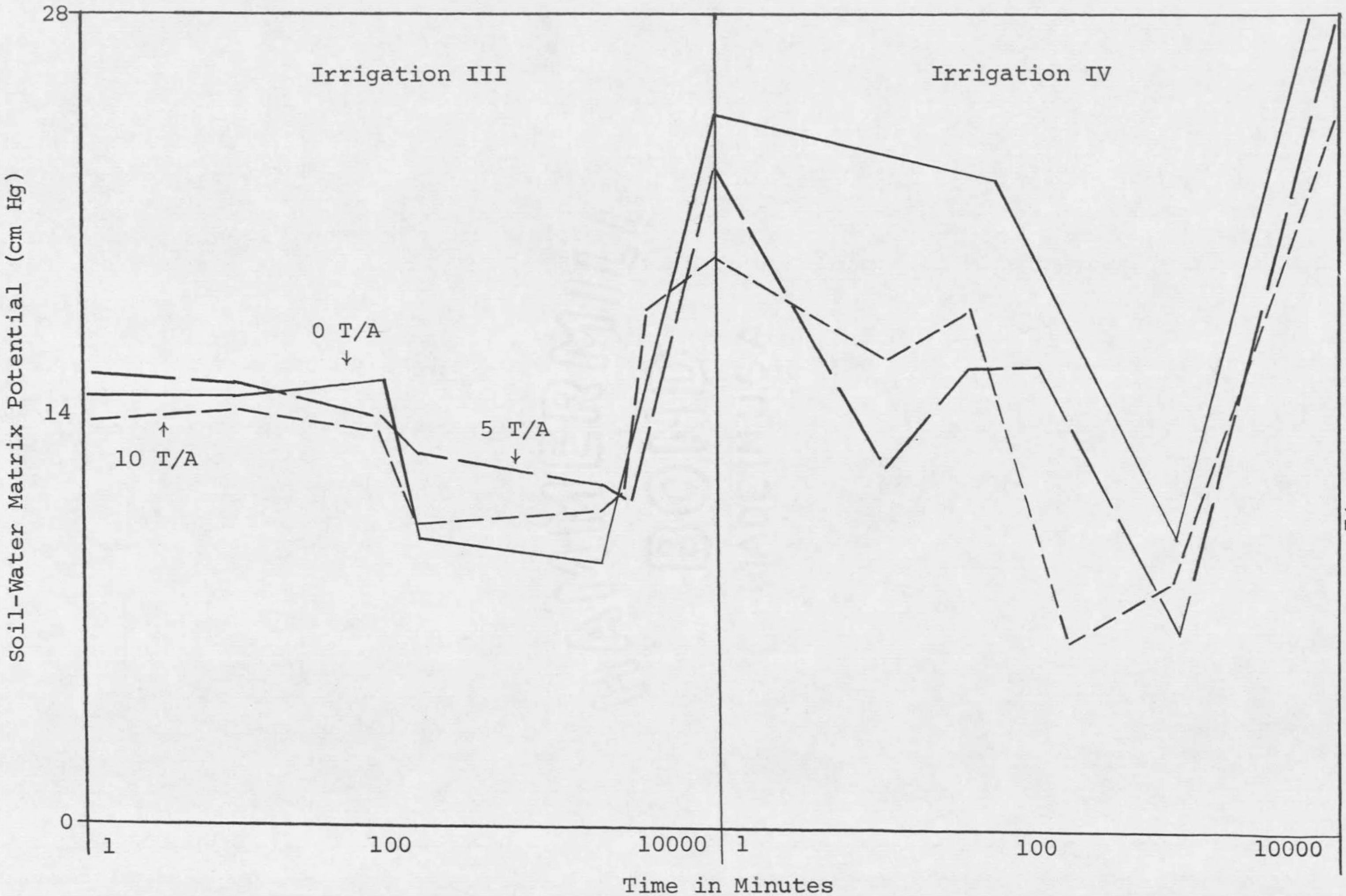


Figure 8b. Semilog plots of soil-water potential at six inch depths during and after 10-day irrigation frequencies as influenced by gypsum rates. Relative infiltration rates can be deduced from the change in tensiometer readings after start of irrigation.

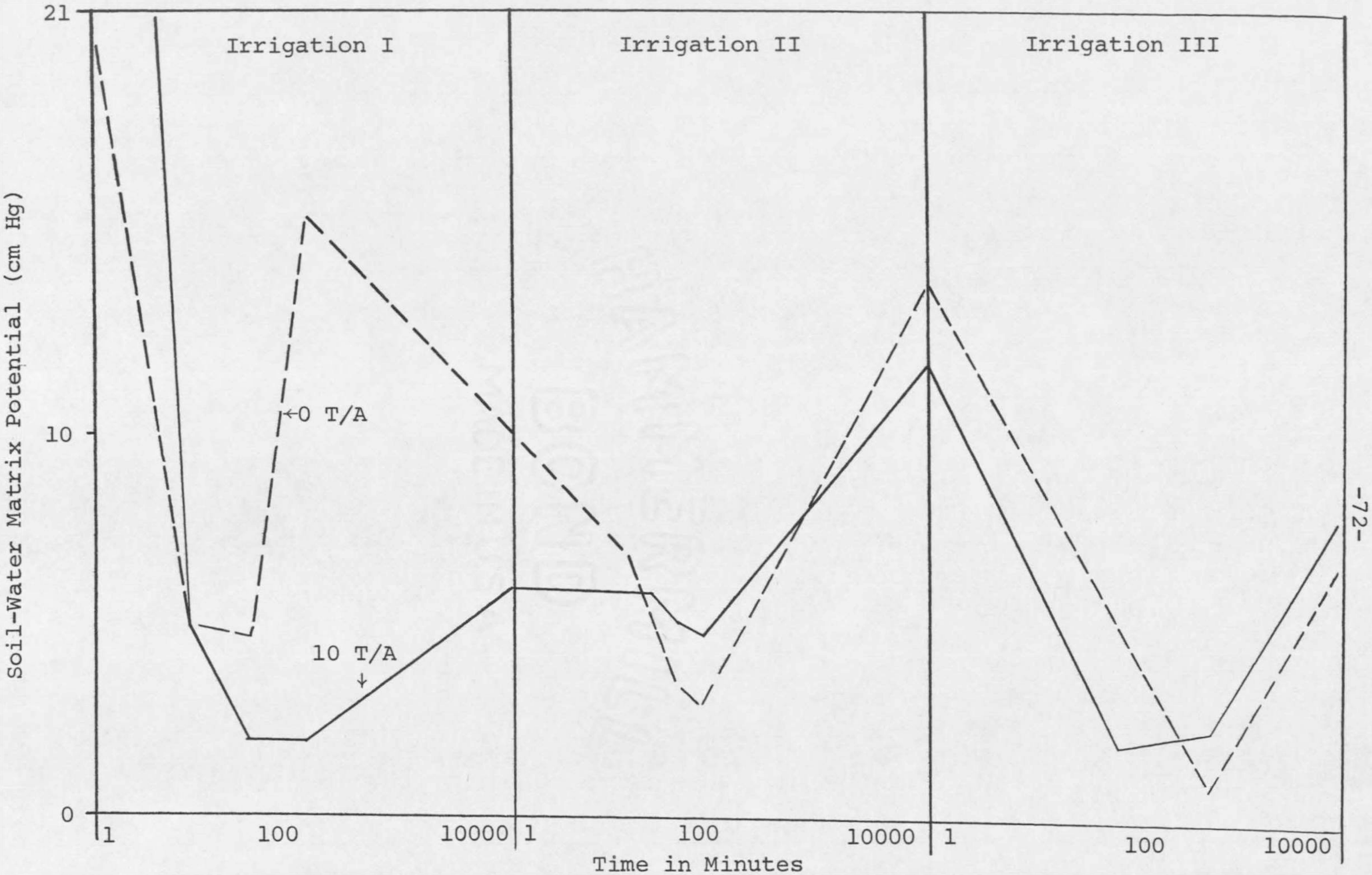


Figure 9a. Semi-log plots of soil-water potential at six inch depths during and after 5-day irrigation frequencies as influenced by gypsum rates. Relative infiltration rates can be deduced from the change in tensiometer readings after start of irrigation.

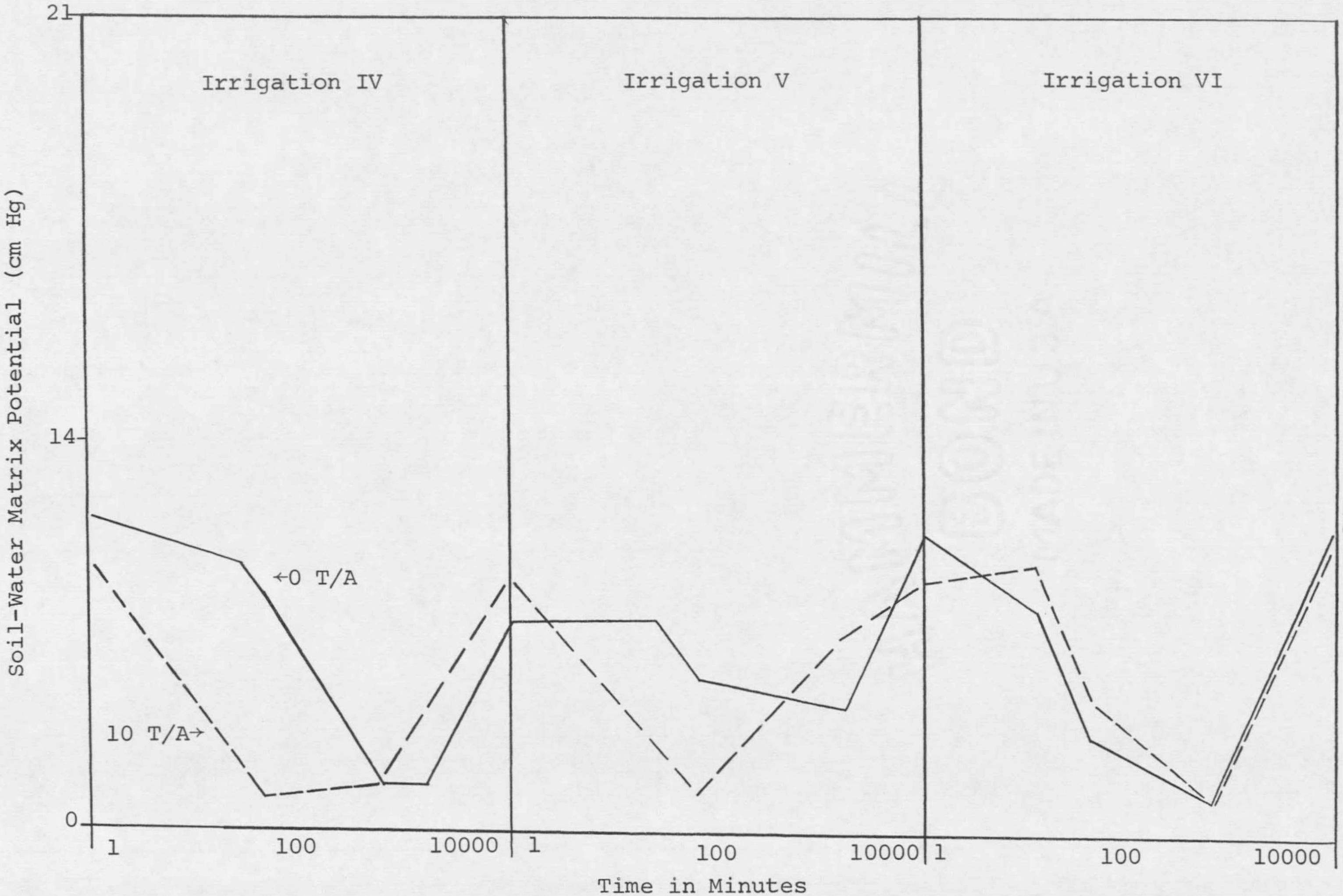


Figure 9b. Semi-log plots of soil-water potential at six inch depths during and after 5-day irrigation frequencies as influenced by gypsum rates. Relative infiltration rates can be deduced from the change in tensiometer readings after start of irrifation.

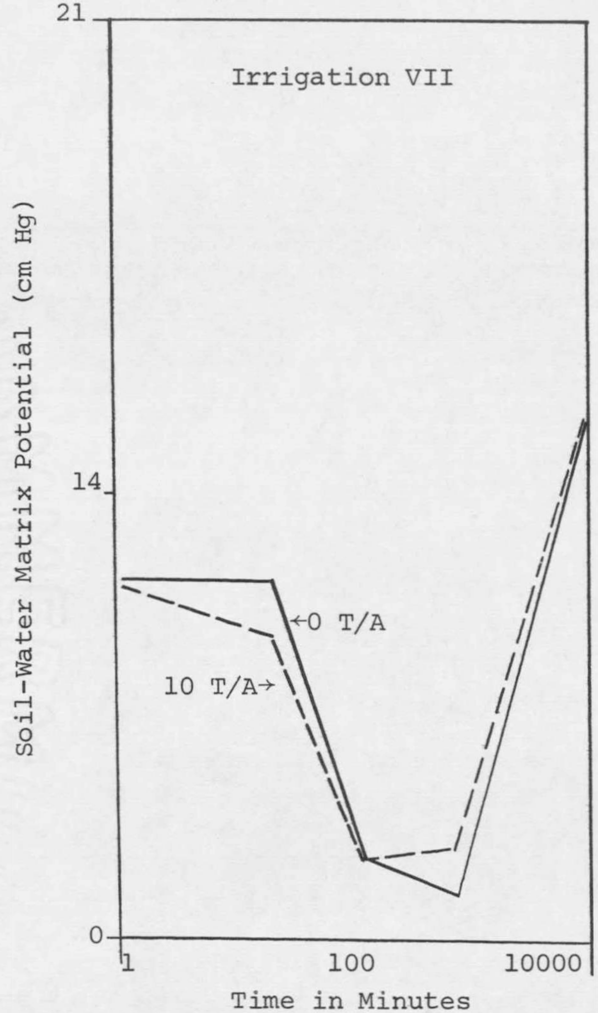


Figure 9c. Semi-log plots of soil-water potential at six inch depths during and after 5-day irrigation frequencies as influenced by gypsum rates. Relative infiltration rates can be deduced from the change in tensiometer readings after start of irrigation.

from the plots in the laboratory using Equation 5.

$$K = \frac{Q\Delta L}{tA\Delta H} \quad [5]$$

where K is the average hydraulic conductivity in cm/hr, Q is the volume of water passing through the soil sample in time (t); ΔL is the length of the soil sample over which there is a hydraulic-head difference (ΔH); A is the area of the soil column.

Hydraulic conductivity measurements of the soil cores were determined using two treatments. First, flow measurements were made using irrigation water, followed by measurements using a saturated gypsum solution. The effect of these two treatments on hydraulic conductivity for various average soil-water potentials is shown in Figures 10a and b for several soil depth. The gypsum treatment clearly increased the hydraulic conductivity of the soil at all soil water tensions. The varying scale magnitude for hydraulic conductivity at the various depths indicate the non-uniform nature of the soil layers, however, the gypsum treatment consistently increased the water transmitting ability of the undisturbed soil cores at all depths. The measured increase in hydraulic conductivity can be attributed to the effect of the calcium ions from gypsum. The calcium ions replaced the sodium ions in the soil system thereby, forming a thinner diffuse layer between soil particles. The thinner diffuse layer tended to flocculate rather than disperse the soil particles thus, opening up the water transmitting pores.

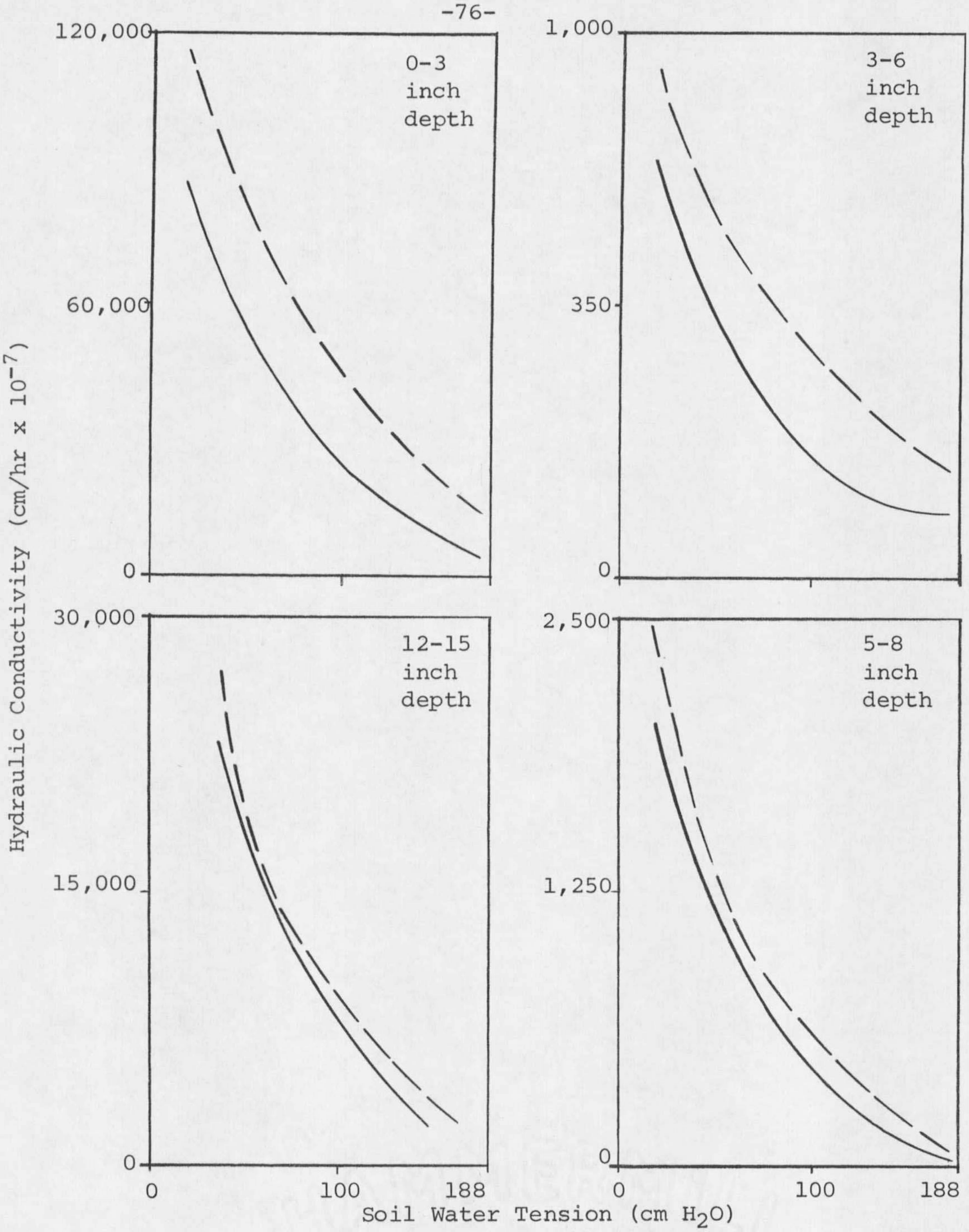


Figure 10a. Hydraulic conductivity, as determined in the laboratory on undisturbed soil cores, is plotted against soil-water tension. The solid line represents irrigation water and the dashed line a saturated gypsum solution.

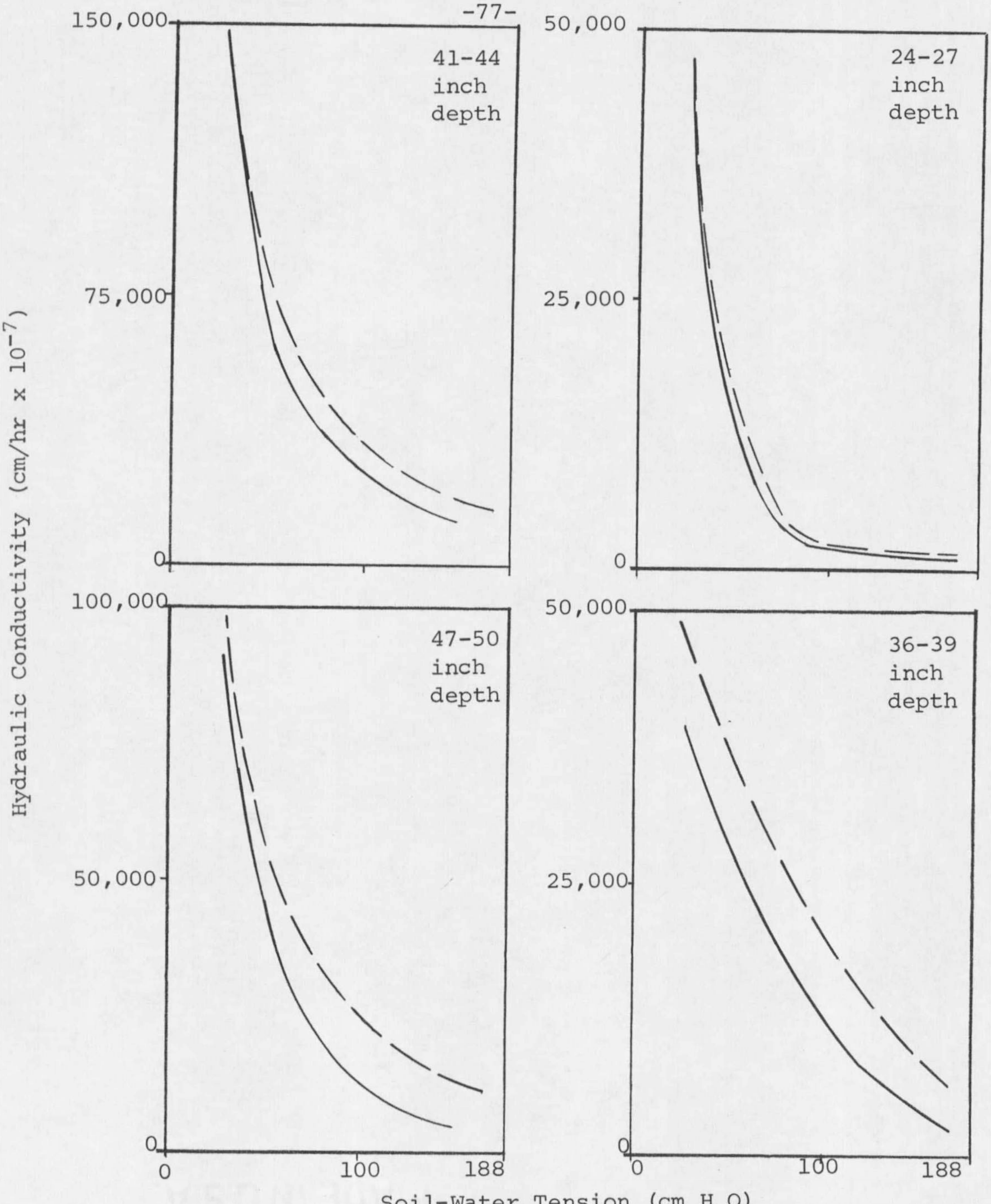


Figure 10b. Hydraulic conductivity, as determined in the laboratory on undisturbed soil cores, is plotted against soil-water tensions. The solid line represents irrigation water and the dashed line a saturated gypsum solution.

Table 14 summarizes the hydraulic conductivity data of figures 10a and b. Hydraulic conductivity ($K_O \rightarrow$irrigation water, $K_G \rightarrow$gypsum solution) values were interpreted from the graphs at three soil-water tensions (27.2, 81.6 and 136 centimeters H_2O), and the corresponding water flux ($Q_O \rightarrow$irrigation water, $Q_G \rightarrow$gypsum solution) was calculated by Equation 5. From these data the percent increase in hydraulic conductivity and water flux due to gypsum was calculated. These results show gypsum increased the ability of the soil to transmit water at all soil depths, and by as much as 2.5 times. This would mean 2.5 times as much water could move through that part of the soil profile, thereby, speeding up the removal of excess salts in the reclamation process of this saline-alkali soil.

It is worth noting that the laboratory technique (58) used to measure hydraulic conductivity in this section required one major assumption as stated in the methods and materials section. It was assumed that the impedance of water flow due to the porous plates on each end of the soil sample was insignificant and was therefore, ignored. A comparison between the laboratory data of Table 14 and the field data of Tables 15, 16, 17, 18, and 19 indicates this assumption to be valid. The magnitude of the K and Q values are the same. From these data it can be concluded that this laboratory technique did not require tensiometer measurements within the undisturbed soil sample.

Table 14. Hydraulic conductivity (K) and water flux (Q) data as determined in the laboratory on undisturbed soil cores. The subscripts "o" and "g" represent no gypsum and gypsum treated samples, respectively. The % increase in K and Q in the laboratory due to the gypsum treatment is calculated at three average soil-water tensions at each soil depth.

depth in inches	average soil-water tension (cm H_2O)	K_o cm/hr x 10^{-4}	K_g cm/hr x 10^{-4}	Q_o cm^3/hr x 10^{-4}	Q_g cm^3/hr x 10^{-4}	% increase in K and Q
0-3	27.2	79.60	107.0	150.4	202.2	34.4
0-3	81.6	39.70	60.7	146.1	223.4	52.9
0-3	136.0	11.00	23.0	60.0	125.6	109.3
3-6	27.2	.0494	.0611	.0934	.1160	24.2
3-6	81.6	.0239	.0335	.0880	.1233	40.1
3-6	136.0	.0088	.0164	.0480	.0895	86.5
5-8	27.2	1.620	2.260	3.060	4.270	39.5
5-8	81.6	.0459	.076	.169	.281	66.5
5-8	136.0	.0083	.025	.046	.136	200.0
12-15	27.2	--	--	--	--	--
12-15	81.6	10.80	11.90	39.70	43.80	10.3
12-15	136.0	2.82	6.74	15.40	36.80	136.0
24-27	27.2	46.53	46.53	87.94	87.94	0.0
24-27	81.6	2.92	4.59	10.75	16.89	57.1
24-27	136.0	1.11	1.53	6.06	8.35	37.8
36-39	27.2	39.70	48.90	75.00	92.4	23.2
36-39	81.6	16.70	25.00	61.50	92.0	49.6
36-39	136.0	4.73	10.80	25.83	58.97	246.4
41-44	27.2	145.6	147.1	275.2	278.0	1.0
41-44	81.6	34.3	40.4	126.3	148.7	17.7
41-44	136.0	13.7	18.8	74.8	102.6	37.2
47-50	27.2	91.53	99.05	173.0	187.2	8.2
47-50	81.6	23.90	30.60	88.0	112.6	28.0
47-50	136.0	5.83	11.10	13.8	60.6	90.4

Hydraulic Conductivity and Water Flux Measurements in the Field

Tensiometer systems and neutron scattering equipment provided the means to measure hydraulic conductivity and water flux within the undisturbed field soil profile using the Equation 7

$$Q = \frac{\Delta\theta}{t} = KA\,\frac{d\Psi}{dx} \quad [7]$$

where K is the hydraulic conductivity (cm/hr), Q is the flux of water (cm^3/hr,) dΨ is the total potential head (cm) equal to the sum of the soil matrix and gravitational potentials, dx is the vertical distance of flow, and θ is the soil-water content (cm^3).

The water measurements were made in two parts, 1) a limited amount of data was collected during irrigation treatments, and 2) seventeen days of comprehensive drainage measurements were made following the completion of irrigation treatments.

Instrumentation problems with the neutron scattering equipment allowed only one set of water flow calculations to be made during irrigation treatments. To supplement this lack of data attempts were made to employ desorption curves (Figures 11 and 12) made from disturbed soil samples on a pressure membrane apparatus which plotted water content (% by weight) against soil-water potential. Potential (Ψ) data from field tensiometers coupled with the desorption curves provided the means for calculating changes in soil-water content (θ) with time. However, the lack of soil bulk density data in conjunction with very small changes in soil-water content with time

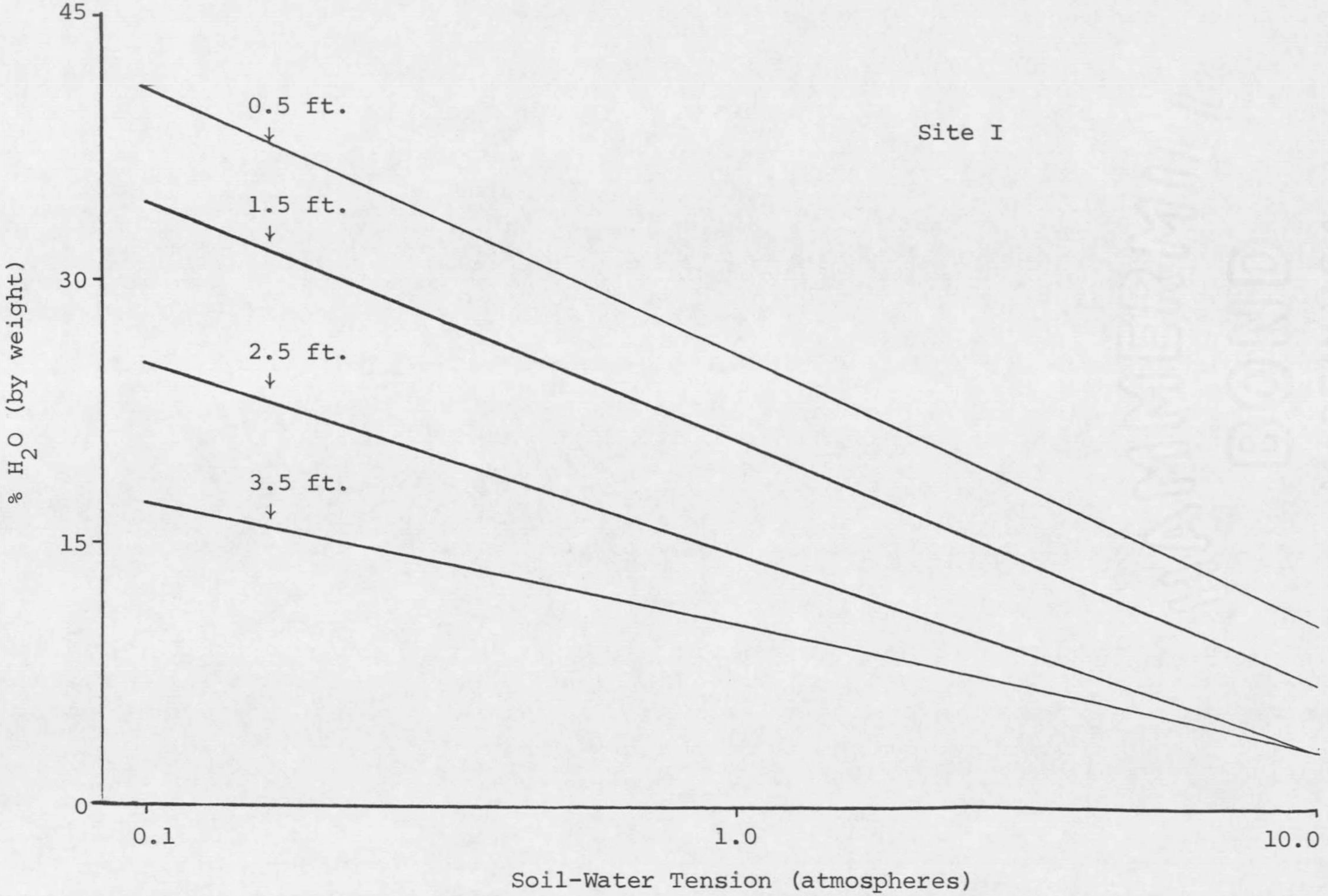


Figure 11. Semi-log desorption lines for the saline and alkali soil profile. The numbers on each line indicate soil depth.

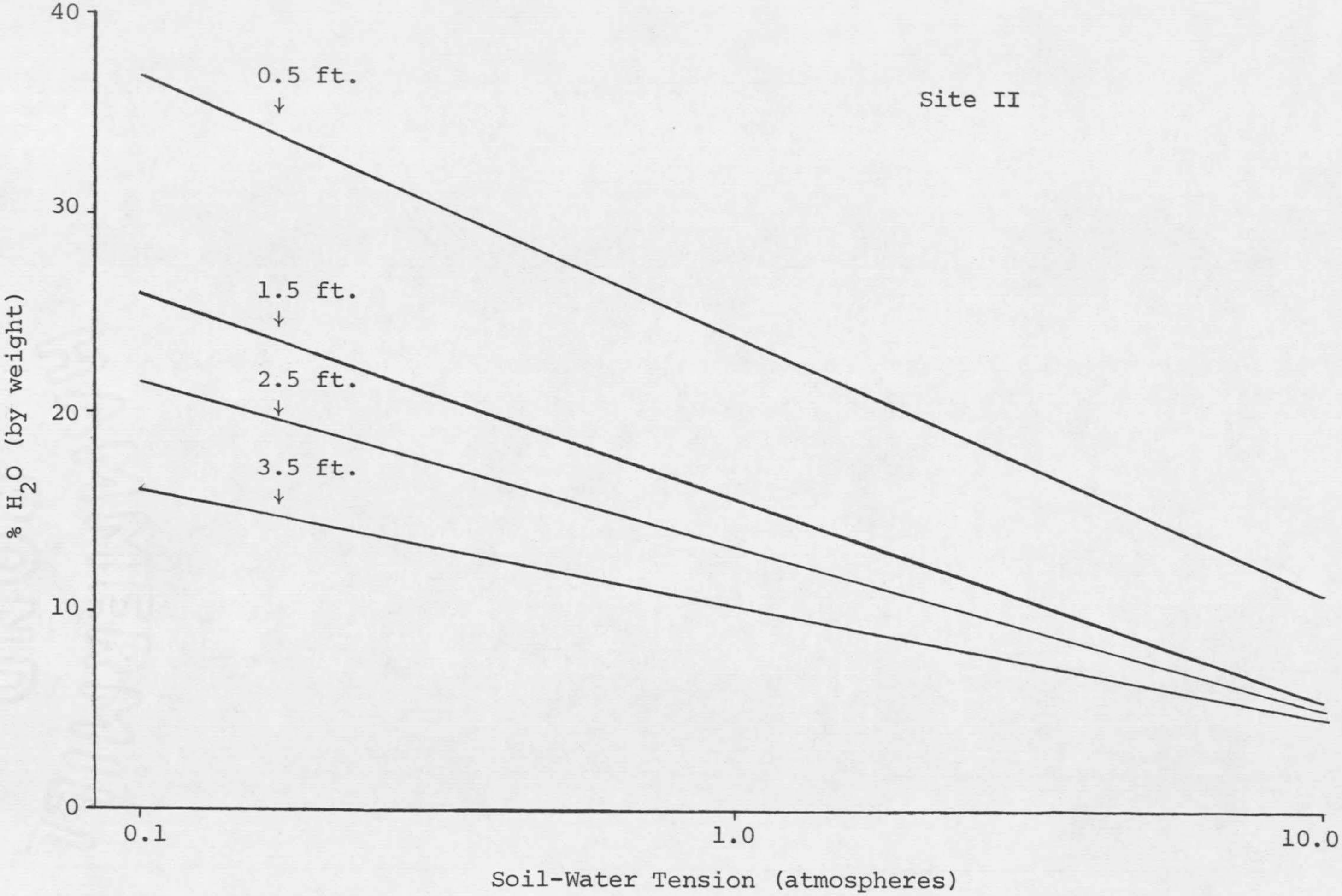


Figure 12. Semi-log desorption lines for the saline and alkali soil profile. The numbers on each line indicate soil depth.

entailed a phenomenally large error associated with this technique. Therefore, calculations employing desorption curves were scrubbed and are not presented. However, the limited data collected during the irrigations proved to be meaningful.

Table 15 represents hydraulic conductivity (K) and water flux (Q) data at two soil depths as a function of gypsum rates, 0- and 10-tons

Table 15. Hydraulic conductivity (K) and water flux (Q) data as calculated from field data. These data are from plots irrigated once every 5-days and the calculated values represent existing conditions between the fourth and fifth irrigation. The differences between K and Q values is a function of the gravitational and matrix potential gradient measured at each soil depth with tensiometers.

depth in feet	Gypsum rate T/A	K (cm/hr)	Q (cm^3/hr)
1	0	1.066×10^{-3}	5.586×10^{-3}
2	0	1.044×10^{-3}	1.230×10^{-3}
1	10	2.249×10^{-3}	13.480×10^{-3}
2	10	2.476×10^{-3}	2.476×10^{-3}

per acre. These data were collected after the fourth irrigation (5-day frequency treatment). The plotted data in Figure 13 demonstrates that gypsum more than doubled the hydraulic conductivity at both depths, and tripled the flux of water moving through the one foot depth. Table 16 represents K and Q data at three soil depths as a function of gypsum rates 0, 5 and 10 tons per acre. These data were collected after the second irrigation (15-day frequency

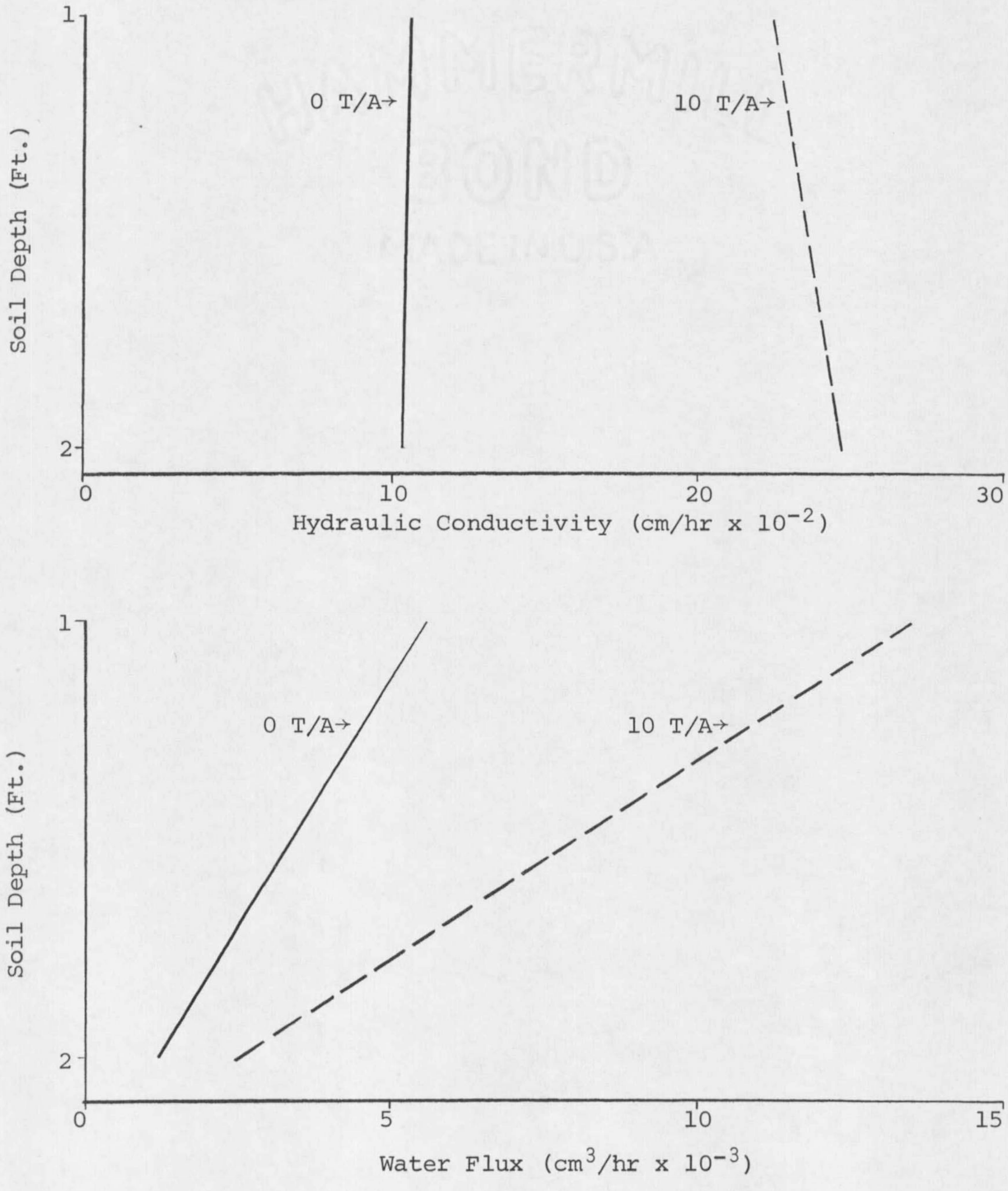


Figure 13. Hydraulic properties of the soil profile as a function of gypsum rates (0 and 10 T/A) for conditions existing between the 4th and 5th irrigations of a 5-day irrigation frequency.

Table 16. Hydraulic conductivity (K) and water flux (Q) data as calculated from field data. These data are from plots irrigated once every 15-days and the calculated values represent conditions existing one day after the second irrigation. The differences between K and Q values is a function of the gravitational and matrix potential gradient measured at each soil depth with tensiometers.

depth in feet	gypsum rate T/A	K (cm/hr)	Q (cm^3/hr)
1	0	1.411×10^{-3}	5.407×10^{-3}
2	0	1.422×10^{-2}	1.327×10^{-2}
3	0	2.549×10^{-2}	2.350×10^{-2}
1	5	2.205×10^{-3}	9.533×10^{-3}
2	5	3.784×10^{-2}	1.927×10^{-2}
3	5	2.996×10^{-2}	2.900×10^{-2}
1	10	3.733×10^{-3}	1.396×10^{-2}
2	10	1.155×10^{-2}	2.906×10^{-2}
3	10	3.128×10^{-2}	2.989×10^{-2}

treatment. The plotted data in Figure 14 demonstrates gypsum consistently increased the hydraulic conductivity at the three depths, and clearly shows a greater water flux with increasing gypsum rates.

Occasionally these data on hydraulic conductivity and water flux have inconsistencies, such as in Figure 14(top) where at the two foot depth 10 T/A gypsum had a lower hydraulic conductivity than no gypsum. Since the changes in water content with time are so small within this profile such inconsistencies can be attributed to several sources of error. However, the major contributor to digressing data is inaccurate readings of field soil matrix potential from the tensiometers. To date tensiometers are the best means of gathering soil matrix potential data, but they are subject to several sources of error, such as:

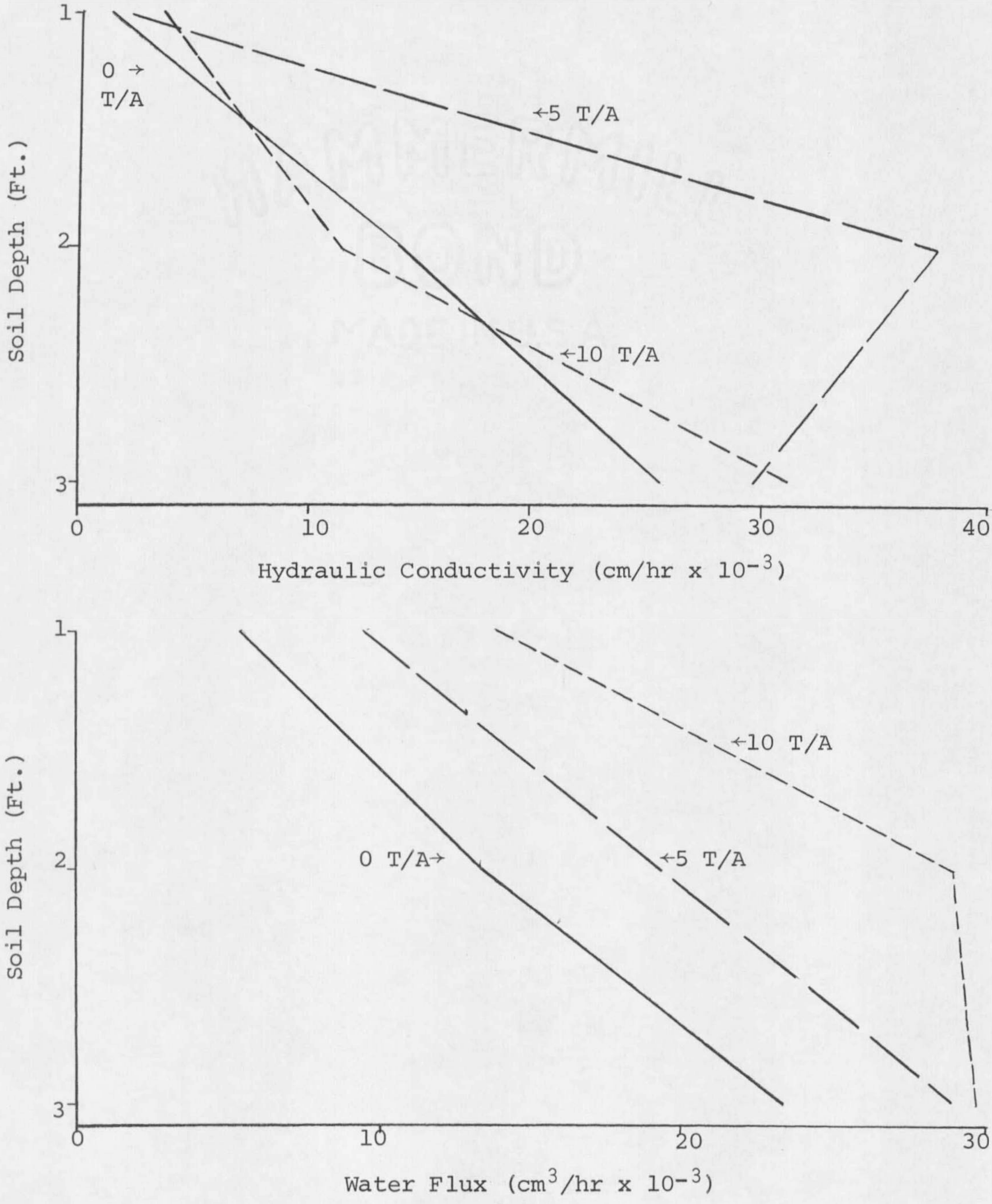


Figure 14. Hydraulic properties of the soil profile as a function of gypsum rates (0-5-10 T/A) for conditions existing one day after the 2nd irrigation of a 15-day irrigation frequency.

1) the mercury columns fluctuate with daily temperature.

2) at tensions above 30 cm H_g air bubbles tend to form in the manometer tubing causing inaccurate readings.

3) at tensions greater than about 60 cm H_g the tensiometer ceases to function.

4) the lag time between the genuine soil-water potential and that read on the manometer is often large.

all these factors have caused some inconsistencies in the following hydraulic conductivity and water flux calculations.

Undeniably, the effect of gypsum upon the water transmitting properties of this saline-alkali soil was present after only a few irrigation treatments. No real comparison can be made concerning the two irrigation frequencies discussed owing to the deficiency of data during this time, however, a comparison of the scale magnitudes in Figures 13 and 14 indicates the plots irrigated once every 5-days had hydraulic conductivity values ten times greater than plots irrigated once every 15-days.

Late in the summer irrigation treatments were completed, and seventeen days of comprehensive water movement measurements followed. The purpose of this was to observe the drainage characteristics of the gypsum treated soil profiles and determine if the gypsum and irrigation treatments increased the ability of this saline and alkali soil to transmit water after being subjected to one summer of reclamation forces.

Hydraulic conductivity (K) and water flux (Q) data for three dates during the seventeen day drainage period are presented in Table 17 (15-day irrigation frequency), Table 18 (10-day irrigation frequency) and Table 19 (5-day irrigation frequency). Table 17 presents data for the 15-day irrigation frequency and is described in Figures 15, 16 and 17. Calculations 45-65 hours into the drainage period (Figure 15) clearly demonstrated gypsum increased the K and Q characteristics of the soil profile. At 70-88 hours into the drainage (Figure 16) the same relationship holds. After 17 days into the drainage (404-427 hours, Figure 17) the flux of water moving through the soil profile was less and error in measurement was correspondingly increased. However, these data still indicate gypsum consistently increased the volume of water moving through the one and two foot soil depths.

Table 18 presents data for the 10-day irrigation frequency and is described in Figures 18, 19 and 20. Calculations at 50-67 hours into the drainage period (Figure 18) again demonstrate gypsum increased the ability of the soil to transmit water, and at this time the 5 ton rate appeared to be more effective than the 10 ton rate. At 194-215 hours into the drainage (Figure 19) the 10 ton rate of gypsum had a greater K than the plots with no gypsum, but the 5 ton rate did not. Water flux (Q) calculations indicated both gypsum rates increased the volume of flow through the one foot depth, but this did not hold true

Table 17. Hydraulic conductivity (K) and water flux (Q) as a function of gypsum treatments was measured in the field. These data represent K and Q values at various times during a drainage period which followed a summer of irrigating these plots once every 15-days. The differences between K and Q values is due to the potential gradient existing in the field.

depth in feet	gypsum rate T/A	time into drainage	K x 10^{-3} (cm/hr)	Q x 10^{-3} (cm^3/hr)
1	0	45-65 hrs	1.069	.564
2	0	"	8.263	7.526
3	0	"	17.960	17.560
1	5	"	9.791	8.153
2	5	"	95.960	15.680
3	5	"	22.960	22.700
1	10	"	8.574	9.912
2	10	"	10.700	14.870
3	10	"	26.610	26.020
1	0	70-88 hrs	1.013	7.155
2	0		5.960	5.295
3	0		13.880	13.880
1	5	"	178.300	18.600
2	5	"	72.880	17.600
3	5	"	35.560	34.770
1	10	"	7.539	18.140
2	10	"	22.870	29.750
3	10	"	63.120	61.710
1	0	404-427 hrs	0.100	2.209
2	0		54.300	2.209
3	0		8.580	8.504
1	5	"	99.420	13.700
2	5	"	3.061	4.861
3	5	"	3.841	3.755
1	10	"	1.068	14.750
2	10	"	3.346	5.462
3	10	"	5.855	5.789

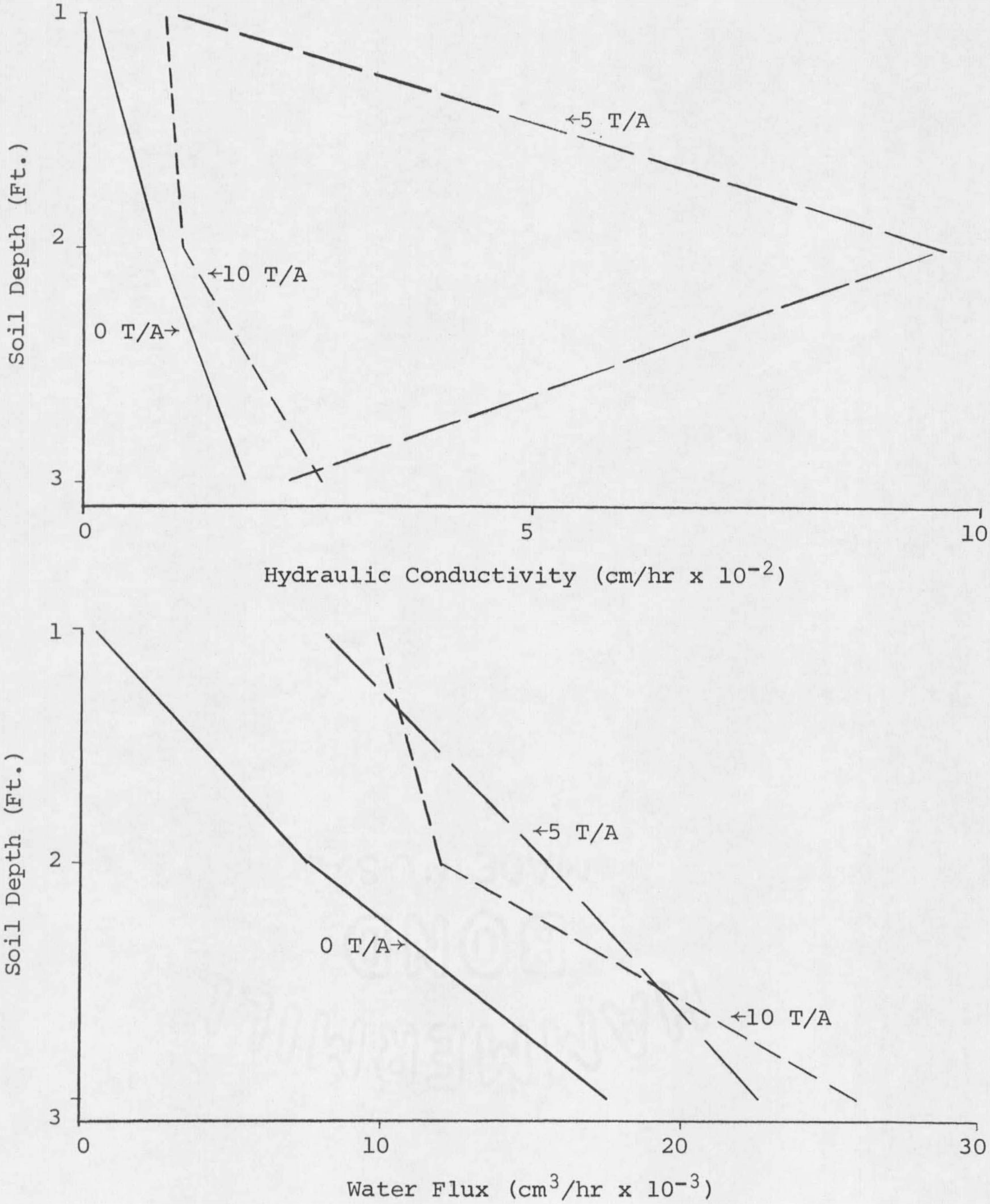


Figure 15. Hydraulic properties of the soil profile as a function of gypsum rates (0,5 and 10 T/A) at 45-65 hours into the drainage period. Plots had a 15-day irrigation frequency.

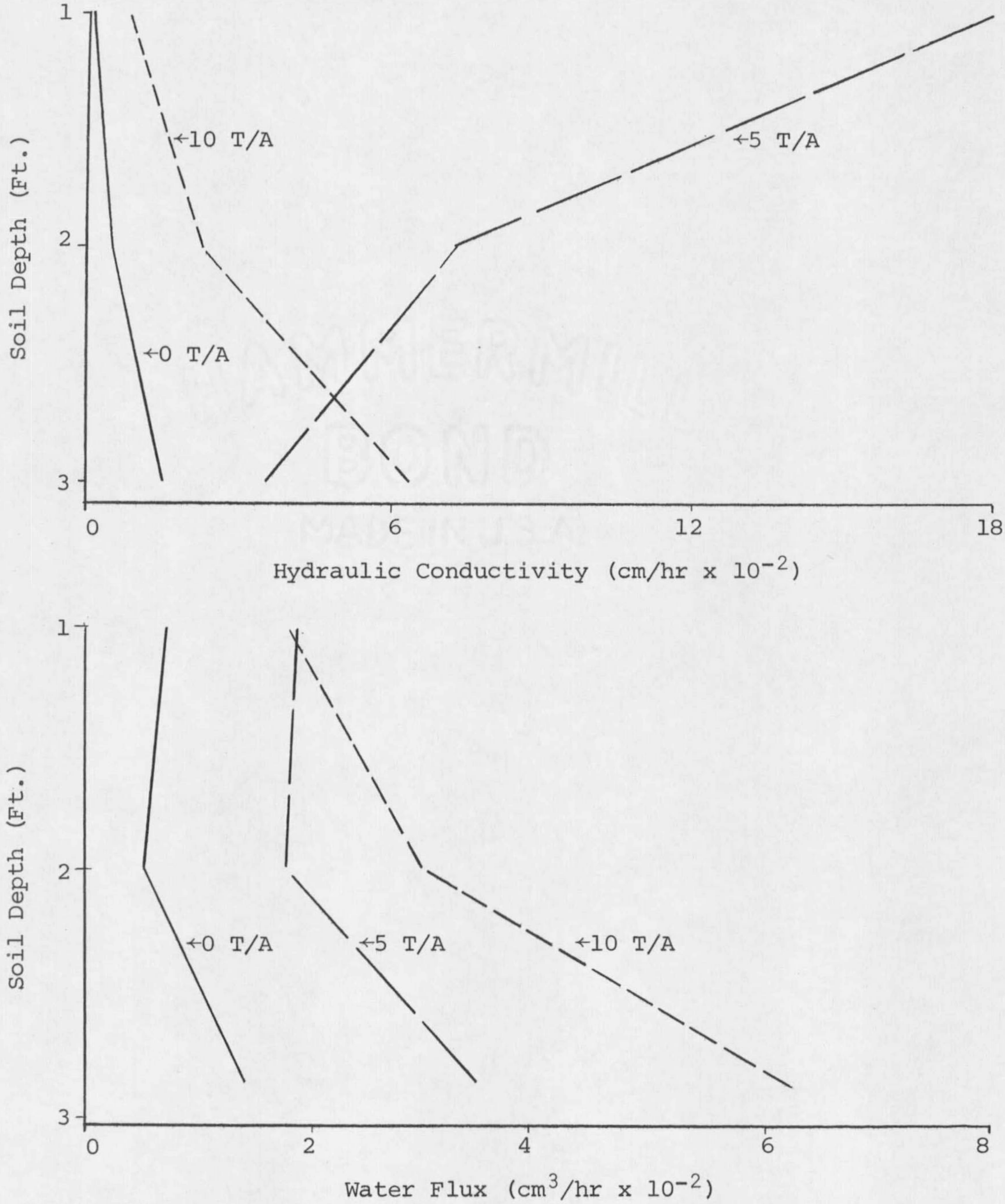
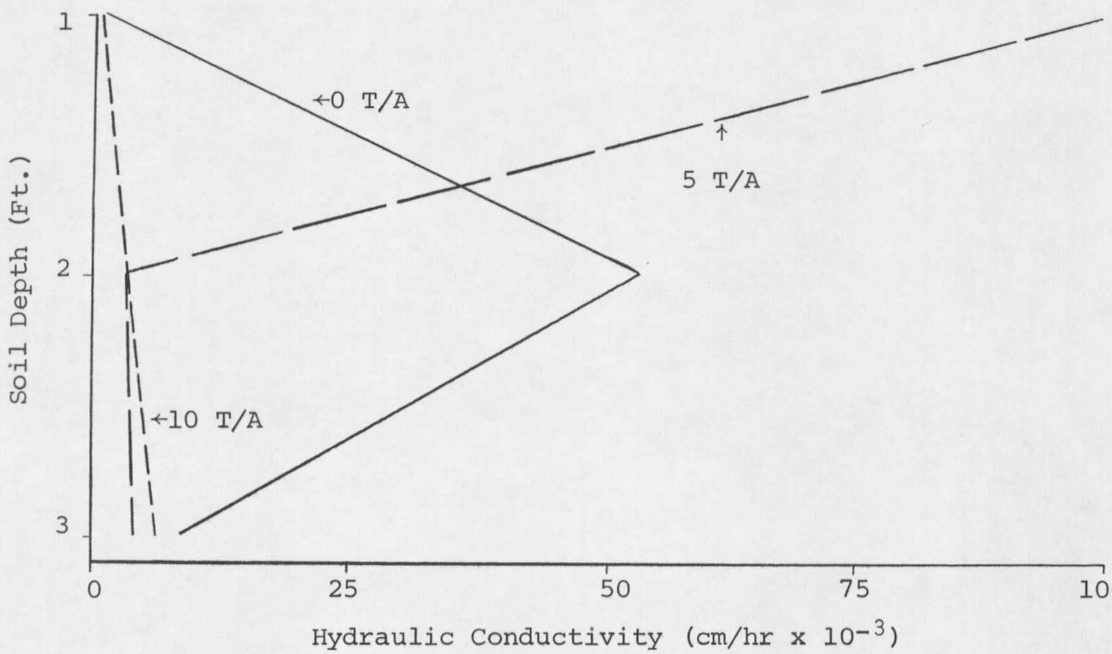


Figure 16. Hydraulic properties of the soil profile as a function of gypsum rates (0, 5 and 10 T/A) at 70-88 hours into the drainage period. Plots had a 15-day irrigation frequency.



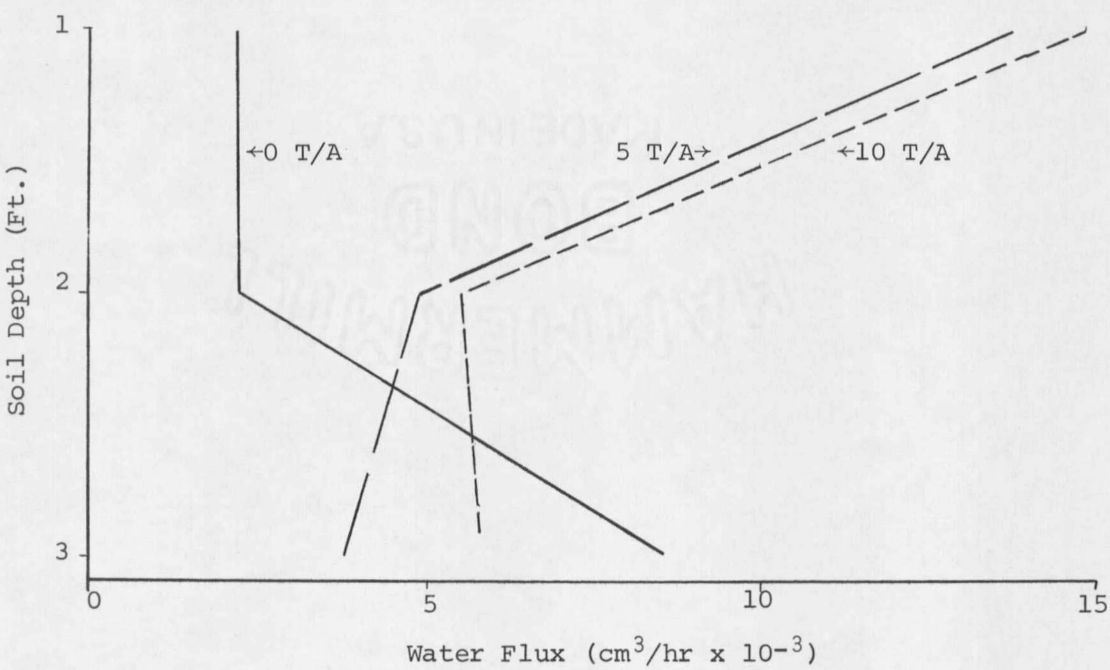


Figure 17. Hydraulic properties of the soil profile as a function of gypsum rates (0, 5 and 10 T/A) at 404-427 hours into the drainage period. Plots had a 15-day irrigation frequency.

Table 18. Hydraulic conductivity (K) and water flux (Q) as a function of gypsum treatments was measured in the field. These data represent K and Q values at various times during a drainage period which followed a summer of irrigating these plots once every 10-days. The difference between K and Q values is due to the potential gradient existing in the field.

depth in feet	gypsum rate T/A	time into drainage	K (cm/hr) x 10^{-3}	Q (cm^3/hr) x 10^{-3}
1	0	50-67 hrs	3.949	2.275
2	0	"	8.340	8.340
3	0	"	16.530	16.530
1	5	"	16.190	25.400
2	5	"	38.190	36.910
3	5	"	33.320	49.310
1	10	"	12.640	11.370
2	10	"	19.370	23.050
3	10	"	36.440	39.280
1	0	194-215 hrs	5.443	5.443
2	0	"	11.340	9.910
3	0	"	20.900	17.660
1	5	"	3.886	8.467
2	5	"	9.412	8.467
3	5	"	12.020	16.570
1	10	"	10.690	11.490
2	10	"	12.830	9.676
3	10	"	19.880	20.560
1	0	260-430 hrs	0.049	0.377
2	0	"	0.206	0.151
3	0	"	0.211	0.211
1	5	"	0.140	0.679
2	5	"	0.063	0.060
3	5	"	0.442	0.423
1	10	"	0.389	1.208
2	10	"	0.592	0.453
3	10	"	0.504	0.498

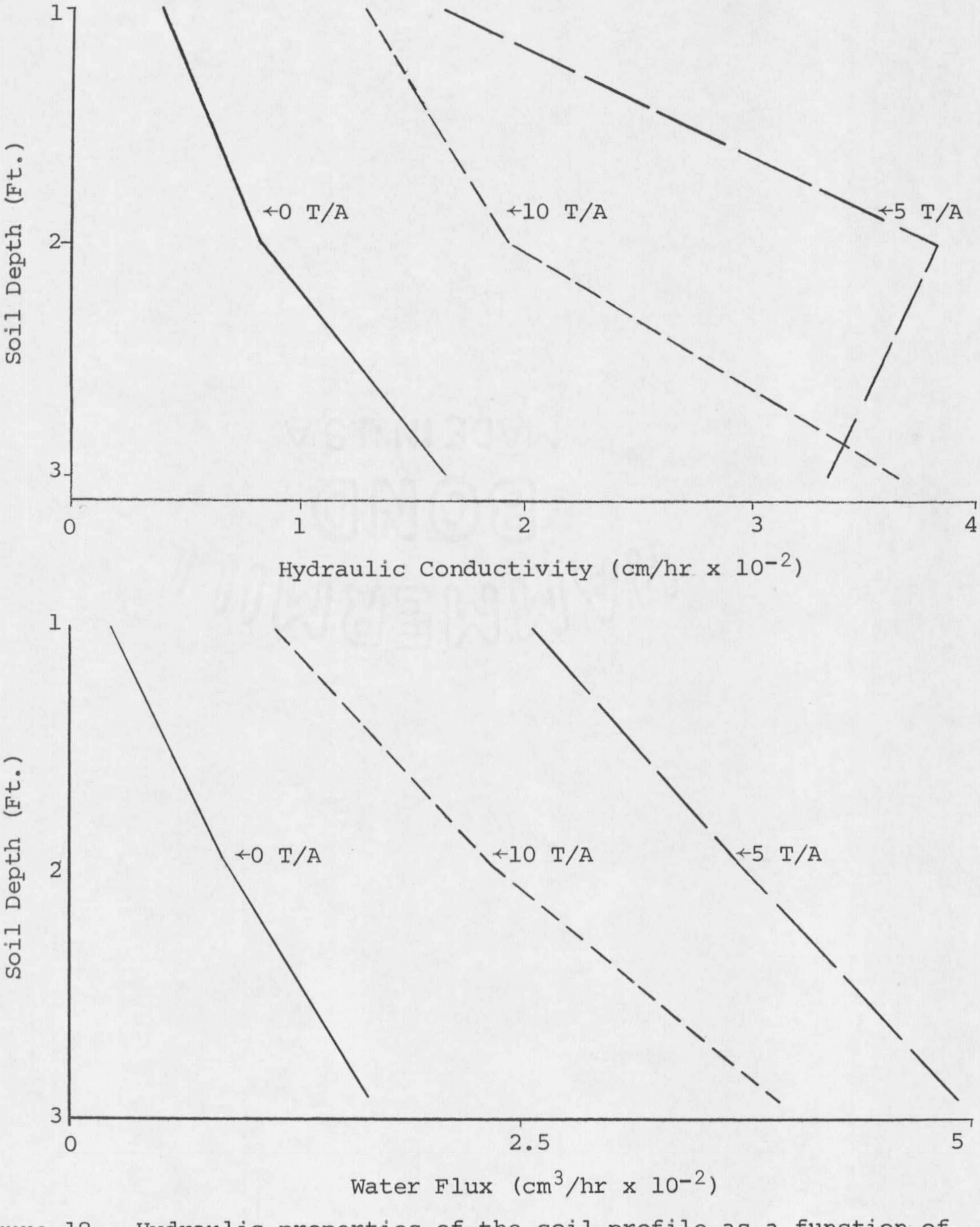


Figure 18. Hydraulic properties of the soil profile as a function of gypsum rates (0, 5 and 10 T/A) at 50-67 hours into the drainage period. Plots had a 10-day irrigation frequency.

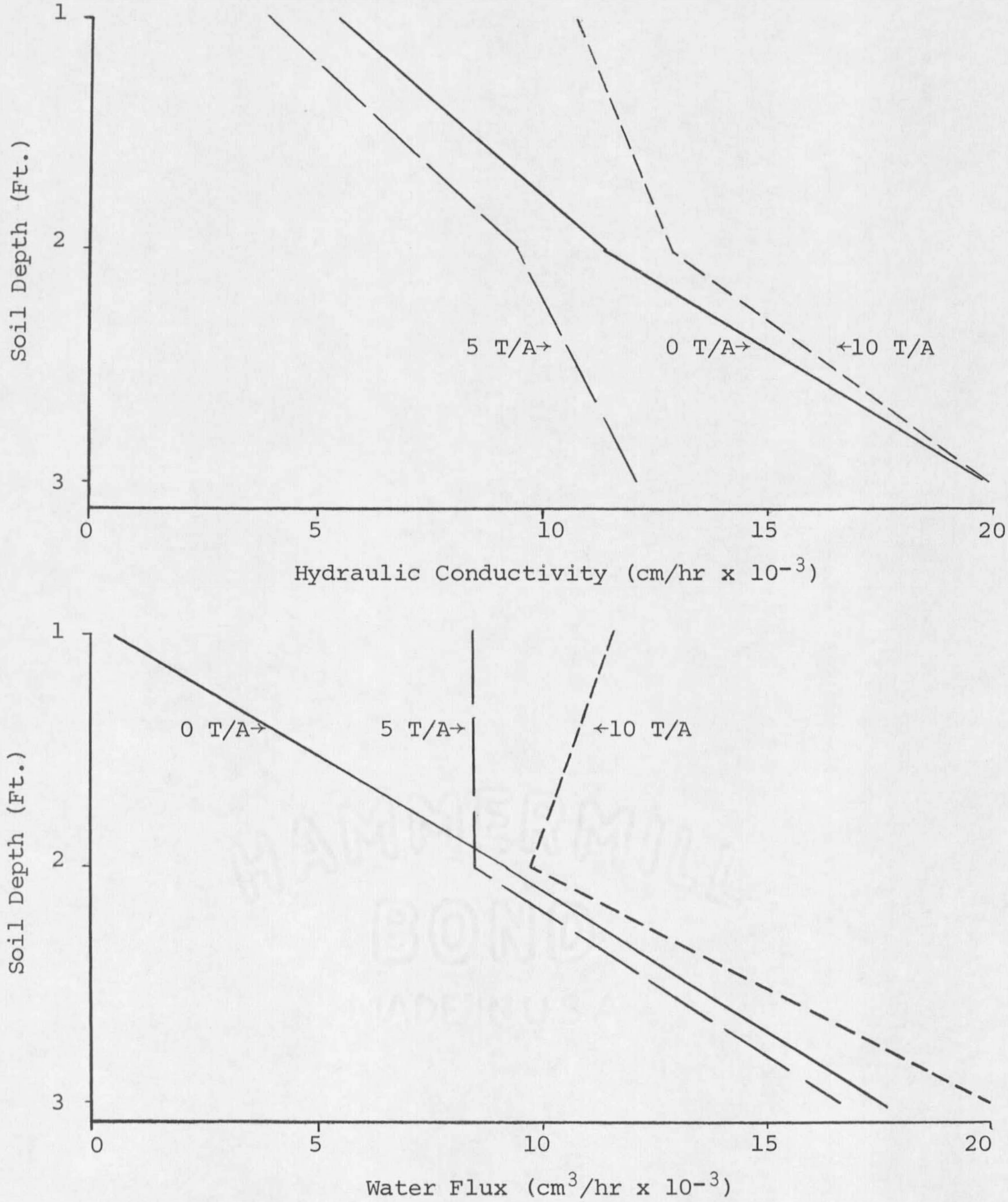


Figure 19. Hydraulic properties of the soil profile as a function of gypsum rates (0, 5 and 10 T/A) at 194-215 hours into the drainage period. Plots had a 10-day irrigation frequency.

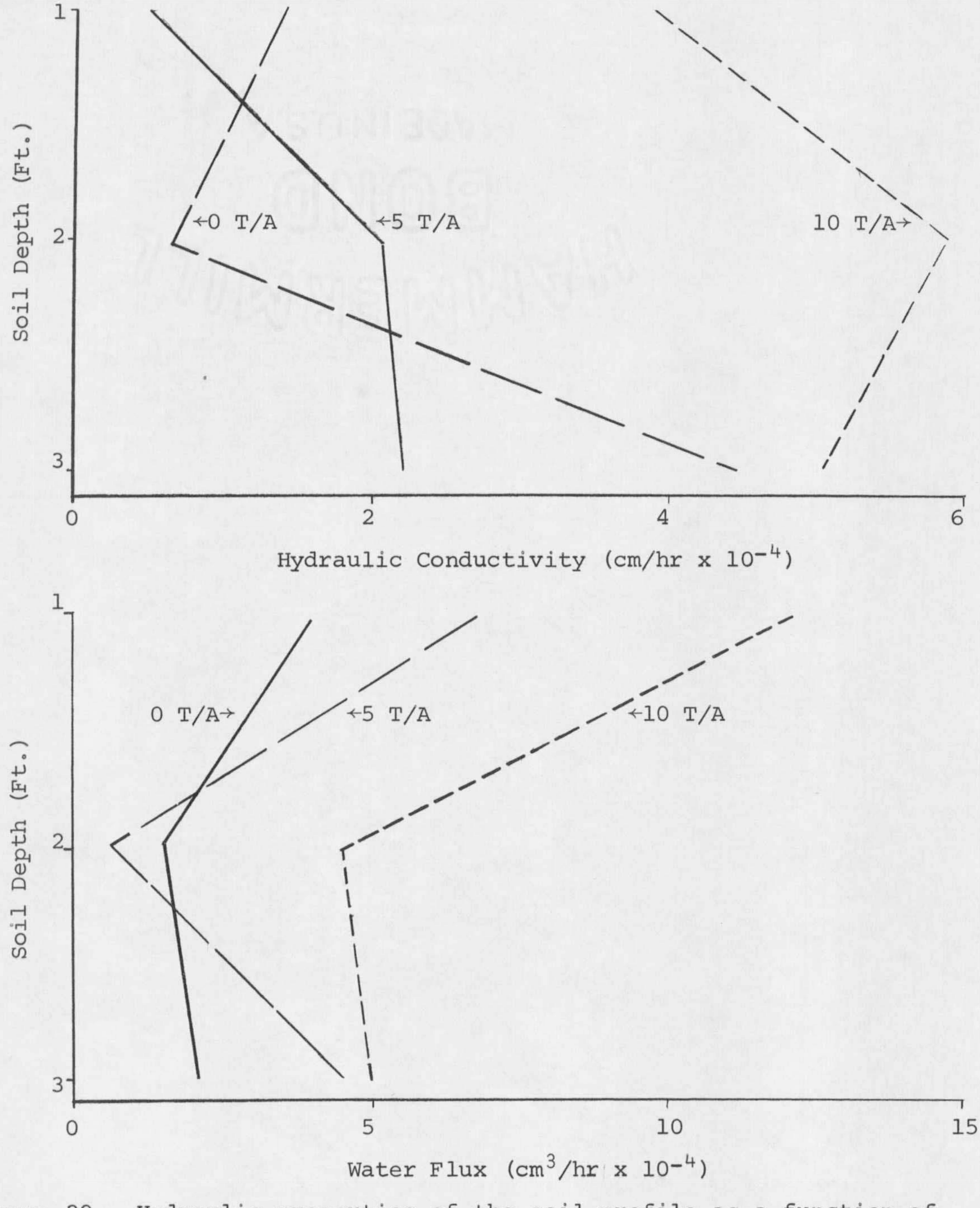


Figure 20. Hydraulic properties of the soil profile as a function of gypsum rates (0, 5 and 10 T/A) at 260-430 hours into the drainage period. Plots had a 10-day irrigation frequency.

for the 5 ton rate at the two and three foot soil depths. During the last part of the drainage test (260-430 hours, Figure 20) both gypsum rates increased the K and Q properties of the soil profile with the exception of the 5 ton rate at two feet. The results of these data for the 10 day frequency irrigation treatment clearly demonstrated 10 tons of gypsum applied per acre increased K and Q values over no gypsum treatment. The 5 ton rate consistently increased the K and Q values of the soil profile, however, the numerous exceptions to this infers 5 tons per acre was not nearly as effective as the 10 ton rate.

Table 19 presents data for the 5-day irrigation frequency and is described in Figures 21, 22, and 23. Calculations were made at 49-66, 215-238 and 405-429 hours into the drainage period. An overall look at the data indicates the effect of gypsum was not as pronounced as in the 15- and 10-day irrigation frequencies. Although the 5 ton rate was not effective in changing the hydraulic properties of the soil profile the 10 ton rate consistently increased the K and Q values of the soil depths.

The results of this field work concerning hydraulic properties of the soil profile as a function of gypsum and irrigation frequency clearly demonstrate gypsum increased the hydraulic conductivity and water flux at all depths of this saline-alkali soil. A relationship was present where the K and Q differences between gypsum and no gypsum was of a decreasing magnitude with more frequent irrigation applications.

Table 19. Hydraulic conductivity (K) and water flux (Q) as a function of gypsum treatments was measured in the field. These data represent K and Q values at various times during a drainage period which followed a summer of irrigating these plots once every 5-days. The difference between K and Q values is due to the potential gradient existing in the field.

depth in feet	gypsum rate T/A	time into drainage	K(cm/hr) x 10^{-3}	Q(cm^3/hr) x 10^{-3}
1	0	49-66 hrs	2.372	11.210
2	0	"	19.320	16.740
3	0	"	19.320	29.580
1	5	"	2.364	10.460
2	5	"	16.810	17.930
3	5	"	40.340	39.890
1	10	"	1.783	7.471
2	10	"	19.690	17.930
3	10	"	40.650	39.290
1	0	215-238 hrs	33.590	30.590
2	0	"	50.670	57.460
3	0	"	85.450	90.240
1	5	"	27.869	27.860
2	5	"	54.740	56.600
3	5	"	80.400	84.340
1	10	"	33.540	34.410
2	10	"	65.420	63.140
3	10	"	98.660	95.140
1	0	405-429 hrs	0.068	0.552
2	0	"	1.577	1.436
3	0	"	2.411	2.540
1	5	"	no data	
2	5	"		
3	5	"		
1	10	"	0.127	1.092
2	10	"	1.096	0.983
3	10	"	6.928	6.774

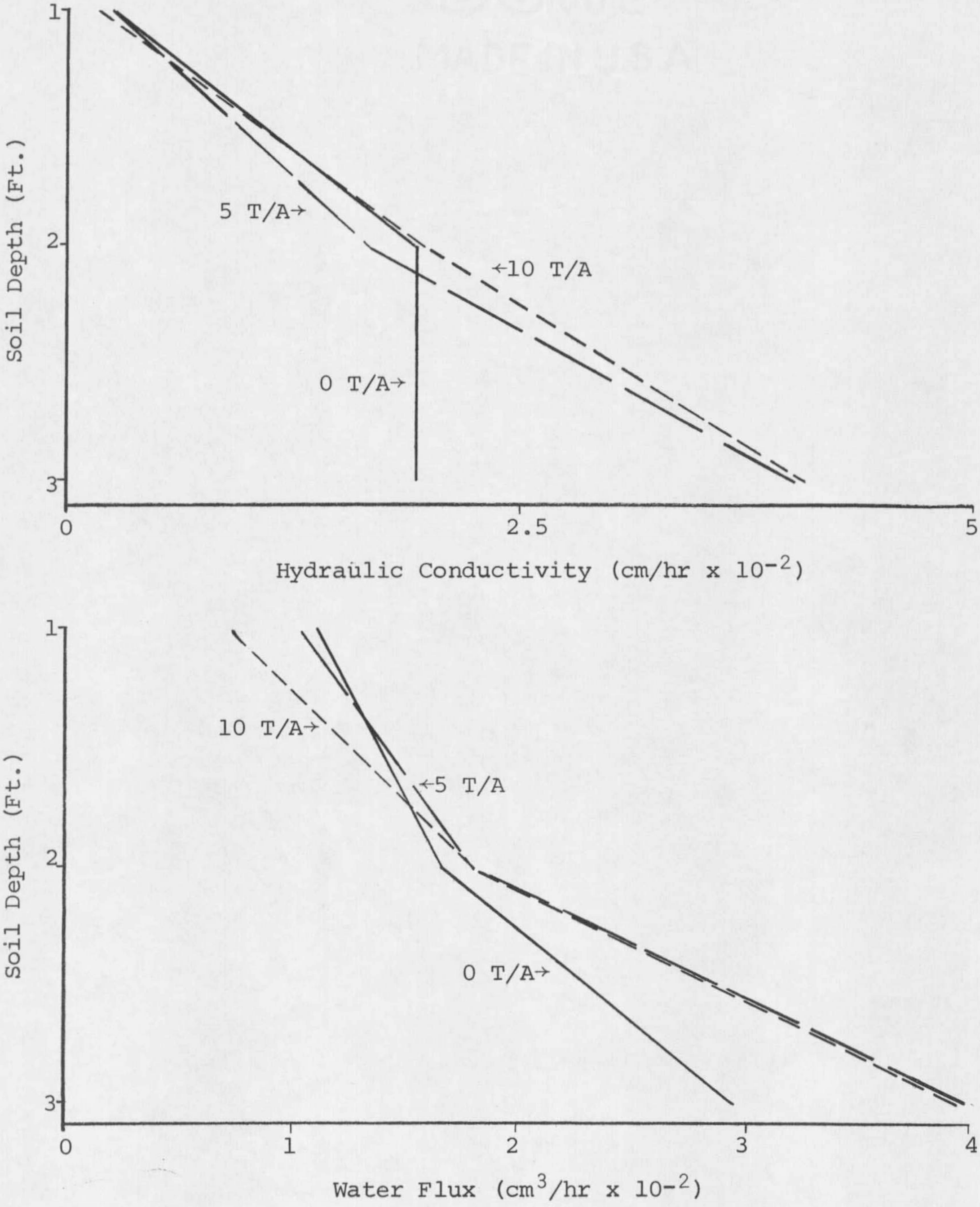


Figure 21. Hydraulic properties of the soil profile as a function of gypsum rates (0, 5 and 10 T/A) at 49-66 hours into the drainage period. Plots had a 5-day irrigation frequency.

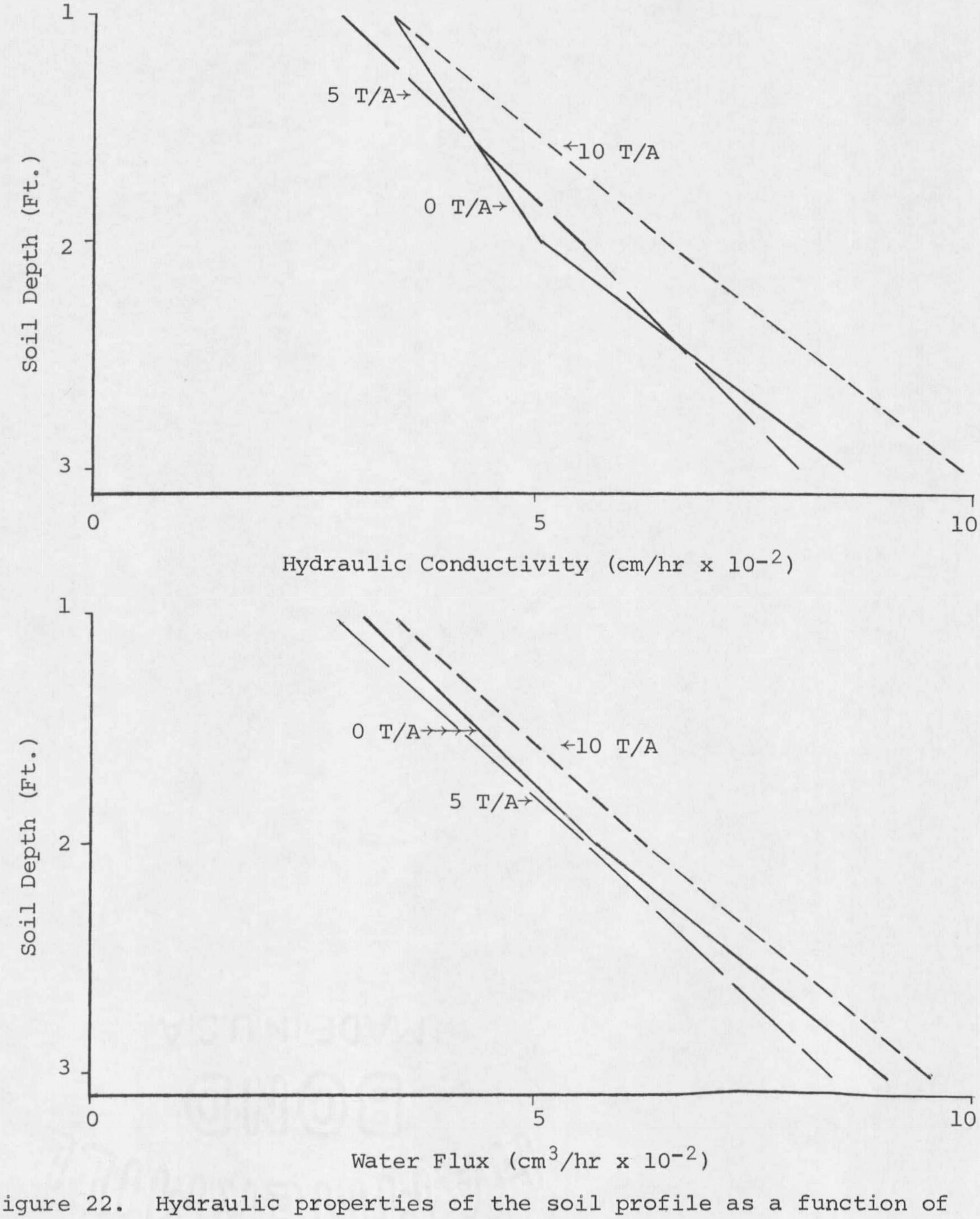


Figure 22. Hydraulic properties of the soil profile as a function of gypsum rates (0, 5 and 10 T/A) at 215-238 hours into the drainage period. Plots had a 5-day irrigation frequency.

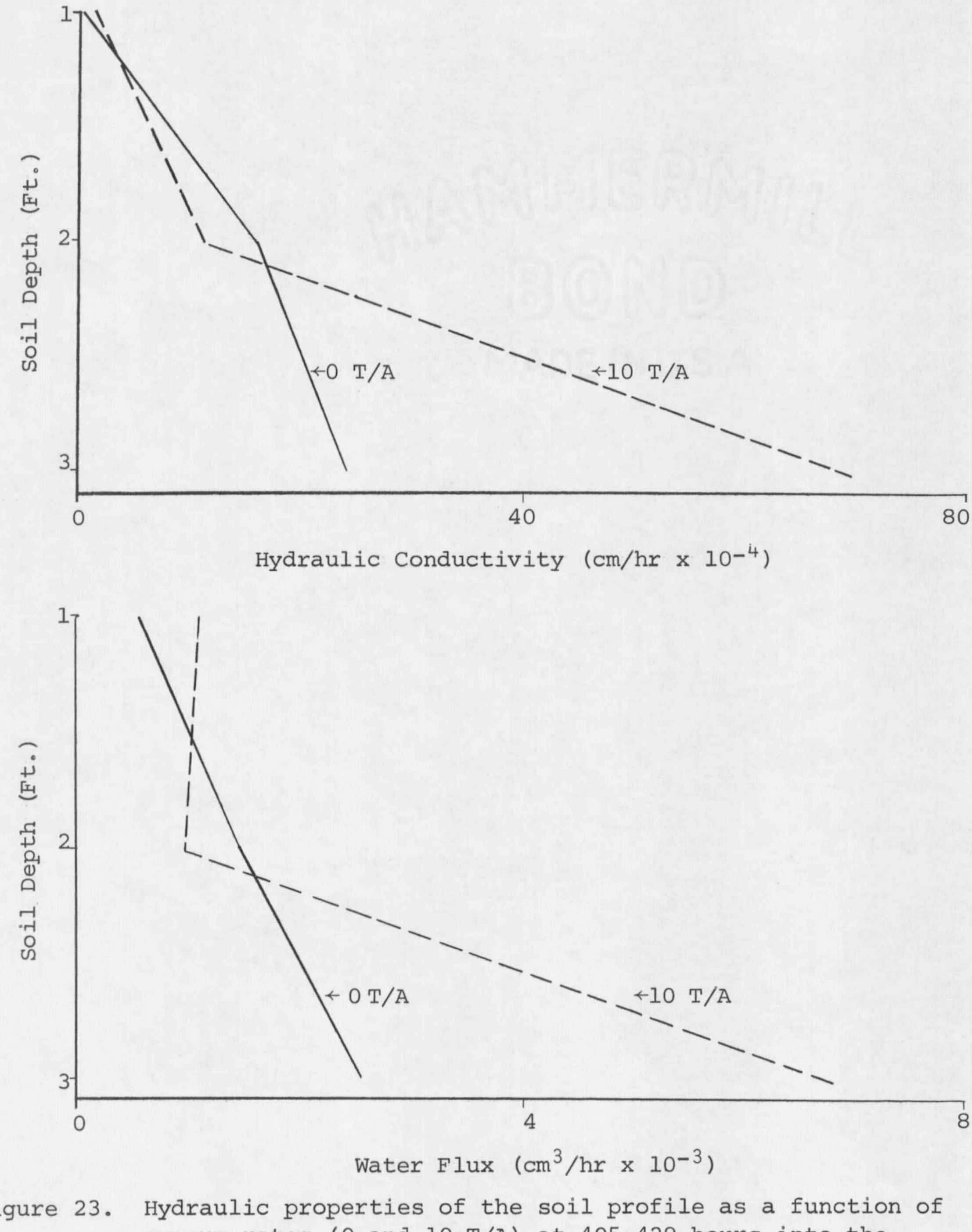


Figure 23. Hydraulic properties of the soil profile as a function of gypsum rates (0 and 10 T/A) at 405-429 hours into the drainage period. Plots had a 5-day irrigation frequency.

For example, data from the 15-day irrigation frequency clearly demonstrated the expected results of gypsum and irrigation treatments, however, data from the 5-day irrigation frequency did not depict the expected results as clearly. This phenomena can be attributed to the greater removal of salts by the 5-day in comparison to the 15-day irrigation frequencies in both the gypsum and non-gypsum treated plots. Thus, the heavier irrigation application tended to mask out the effects of gypsum. No attempt is made to imply irrigation alone was effective in reclaiming this soil, for this is not the case, however the validity of this notion is favorably demonstrated in the following soil chemical analysis results.

Soil Chemical Analsyis

Extensive water movement measurements were made in the field and laboratory to record the effect of gypsum and irrigation regimes on soil hydraulic properties. Results discussed have demonstrated gypsum with irrigation increased the rate and volume of water moving through this saline-alkali soil profile.

To determine if the increased water flow resulted in salt and sodium removal soil samples were taken to a depth of five feet before and after treatments and analysed for electrical conductivity and soluble sodium, calcium, magnesium and potassium (Table 20). From these tables the sodium-adsorption-ratio(SAR) was calculated in order to observe the changes in sodium levels relative to the other cations.

The sodium-adsorption-ratio is a useful means of evaluating the reclamation of sodium affected soils and was calculated for all soil samples by Equation 6

$$SAR = \frac{[Na]}{\sqrt{([Ca] + [Mg])/2}} \quad [6]$$

where the ion concentrations are in millequivalents per liter.

Table 21 presents sodium-adsorption-ratio(SAR) data which is graphed in Figures 24ab and 24c. As depicted in these figures, gypsum lowered the SAR to a greater extent than plots without gypsum. This held true, without exception, through three feet in depth. Soil depths of four and five feet were zones of accumulation, and as a consequence the SAR generally increased. This means that the calcium of gypsum replaced sodium in the soil solution and cation exchange sites, resulting in sodium leaching downward to the three and four foot depths or completely out of the soil profile. A comparison of the irrigation frequencies and scale magnitude of these diagrams indicates the 5-day frequency was much more effective than either the 10- or 15-day frequencies in lowering the SAR and that the 10- and 15-day frequencies were equally effective.

This change in the SAR is responsible for the measured increase in hydraulic properties within the soil profile, as described earlier in the results and discussion. The presence of a smaller Na:Ca ratio, as indicated by a lower SAR, caused the diffuse layers to

Table 20. Chemical analysis of soil samples taken before and after gypsum plus irrigation treatments

depth in feet	Na ppm before	Na ppm after	Ca ppm before	Ca ppm after	Mg ppm before	Mg ppm after	K ppm before	K ppm after
5 day irrigation-10 ton treatment								
1	7700	3200	275	495	220	430	41	29
2	6100	4400	325	425	545	1035	33	23
3	4900	4100	295	395	345	1035	26	25
4	4800	7300	375	445	545	850	20	17
5	1950	4000	280	325	430	620	25	26
5 day irrigation-5 ton treatment								
1	5200	3500	260	350	345	385	36	26
2	4400	3000	300	370	450	510	42	36
3	8400	6800	300	350	650	545	44	37
4	3200	3700	290	325	295	320	35	37
5	2400	3800	280	290	275	310	24	26
5 day irrigation-0 ton treatment								
1	5700	4700	300	325	385	345	29	25
2	5400	4700	295	290	700	510	26	29
3	6000	5500	325	315	600	570	24	18
4	4500	3800	325	325	1035	675	19	20
5	4100	4500	315	300	675	700	27	26
10 day irrigation-10 ton treatment								
1	5800	3800	275	400	450	620	33	30
2	5000	3600	300	375	480	620	25	22
3	6800	4700	290	350	240	250	24	25
4	3800	3700	340	335	430	430	26	27
5	2800	4400	280	315	310	525	20	17
10 day irrigation-5 ton treatment								
1	7800	6100	375	475	510	620	43	38
2	7400	4700	350	375	525	600	40	34
3	4700	3800	325	360	400	545	33	36
4	7200	4100	360	325	1035	400	36	33
5	2400	5500	325	400	385	450	38	39

(continued)

Table 20 (continued).

depth in feet	Na ppm before	Na ppm after	Ca ppm before	Ca ppm after	Mg ppm before	Mg ppm after	K ppm before	K ppm after
10 day irrigation-0 ton treatment								
1	7200	6100	295	325	370	430	35	26
2	6100	6000	355	325	385	370	29	25
3	4600	3800	375	386	525	480	23	18
4	3600	4200	300	335	430	470	25	26
5	2900	3200	385	270	295	285	26	29
15 day irrigation-10 ton treatment								
1	6000	5200	325	450	320	360	48	44
2	5200	4400	335	395	410	570	33	30
3	7200	4900	380	395	450	480	32	25
4	3800	3600	355	340	620	510	23	17
5	2700	3400	250	275	360	345	28	25
15 day irrigation-5 ton treatment								
1	4900	3700	375	425	410	510	39	37
2	6100	5300	325	395	510	546	26	23
3	5500	4000	370	415	480	600	20	23
4	4700	1700	335	325	675	620	27	26
5	2800	3000	315	335	430	400	17	20
15 day irrigation-0 ton treatment								
1	4700	7100	335	350	765	650	34	38
2	4200	5800	280	290	675	725	38	37
3	6600	4800	340	350	570	430	26	25
4	4800	4400	340	315	570	525	23	24
5	3600	3500	275	355	345	310	26	20

Table 21. Sodium-adsorption-ratio(SAR) data from before and after irrigation treatments as a function of gypsum rates and irrigation frequency.

depth in feet	Gypsum rate tons per acre 0			5			10		
	before	after	ΔSAR	before	after	ΔSAR	before	after	ΔSAR
5-day irrigation frequency									
1	51.4	43.3	-8.1	49.8	30.7	-19.1	84.1	25.4	-58.7
2	39.1	38.5	-0.6	37.5	23.8	-13.7	48.0	26.2	-21.8
3	45.6	42.8	-2.8	62.5	53.0	- 9.5	45.9	24.6	-21.3
4	27.5	27.6	0.1	31.6	34.9	3.3	37.1	46.8	9.7
5	29.9	32.5	2.6	24.4	37.0	12.6	17.1	30.0	12.9
10-day irrigation frequency									
1	65.9	52.3	-13.6	61.7	43.4	-18.3	50.1	27.8	-22.3
2	53.5	54.0	0.5	58.5	35.0	-23.5	41.7	26.5	-15.2
3	36.0	30.5	5.5	41.3	29.5	-11.8	71.6	46.9	-24.7
4	31.2	34.7	3.5	43.7	36.0	- 7.7	32.3	31.5	- 0.8
5	27.1	32.4	5.3	21.3	44.8	23.5	27.4	35.3	7.9
15-day irrigation frequency									
1	32.4	51.9	19.5	41.6	28.7	-12.9	56.6	44.3	-12.3
2	31.0	41.5	10.5	49.2	40.6	- 8.6	45.0	33.2	-11.8
3	50.8	40.6	-10.2	44.4	29.4	-15.0	59.2	39.2	-20.0
4	36.9	35.3	- 1.6	34.1	12.8	-21.3	28.2	28.9	0.7
5	34.2	32.8	- 1.4	24.1	26.2	2.1	25.6	32.3	6.7

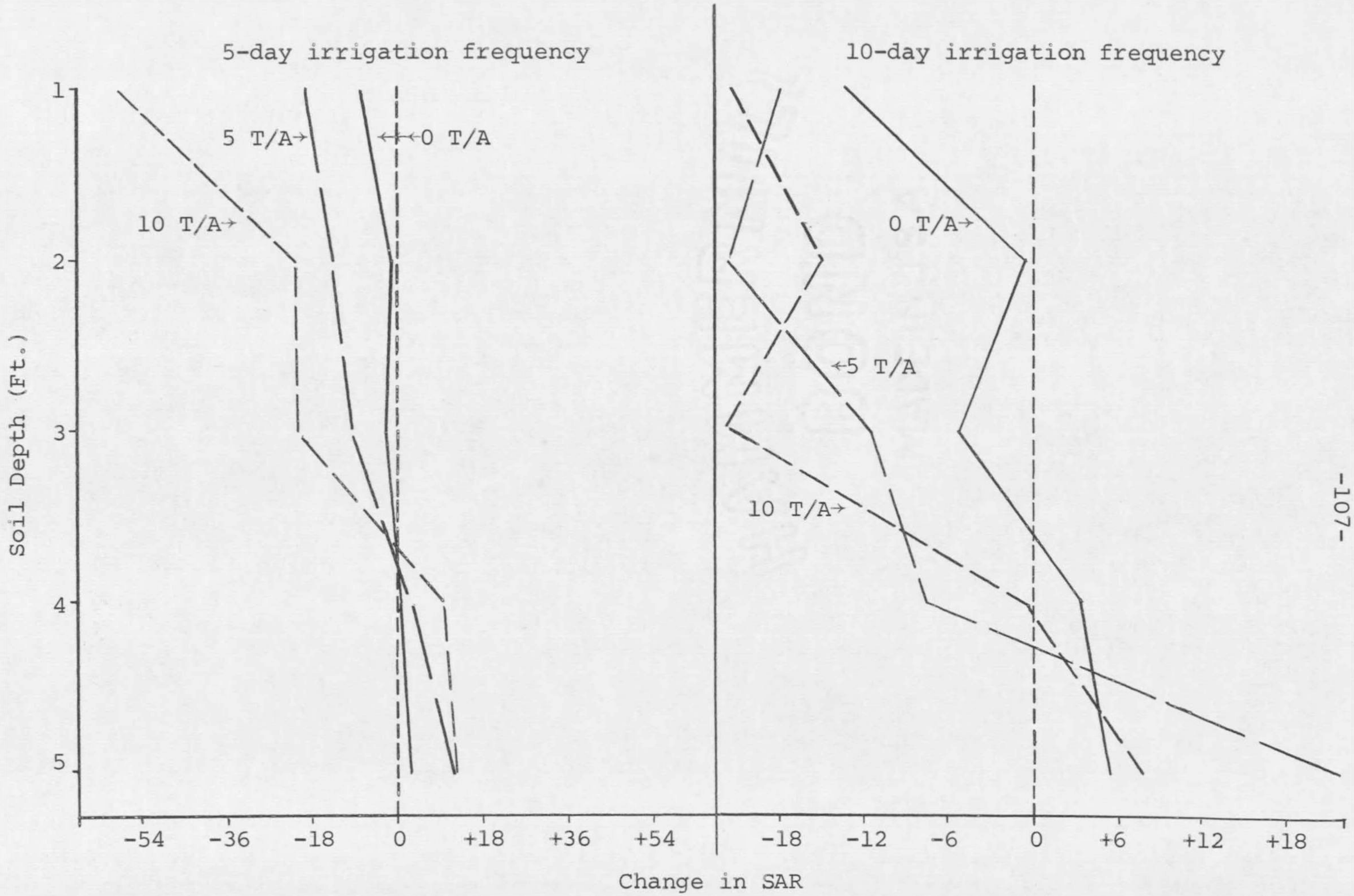


Figure 24ab. The change in sodium-adsorption-ratio (SAR) with depth as a function of gypsum rates (0, 5 and 10 tons per acre) and irrigation frequency is described. The SAR is described at each depth as decreasing (negative) or increasing (positive).

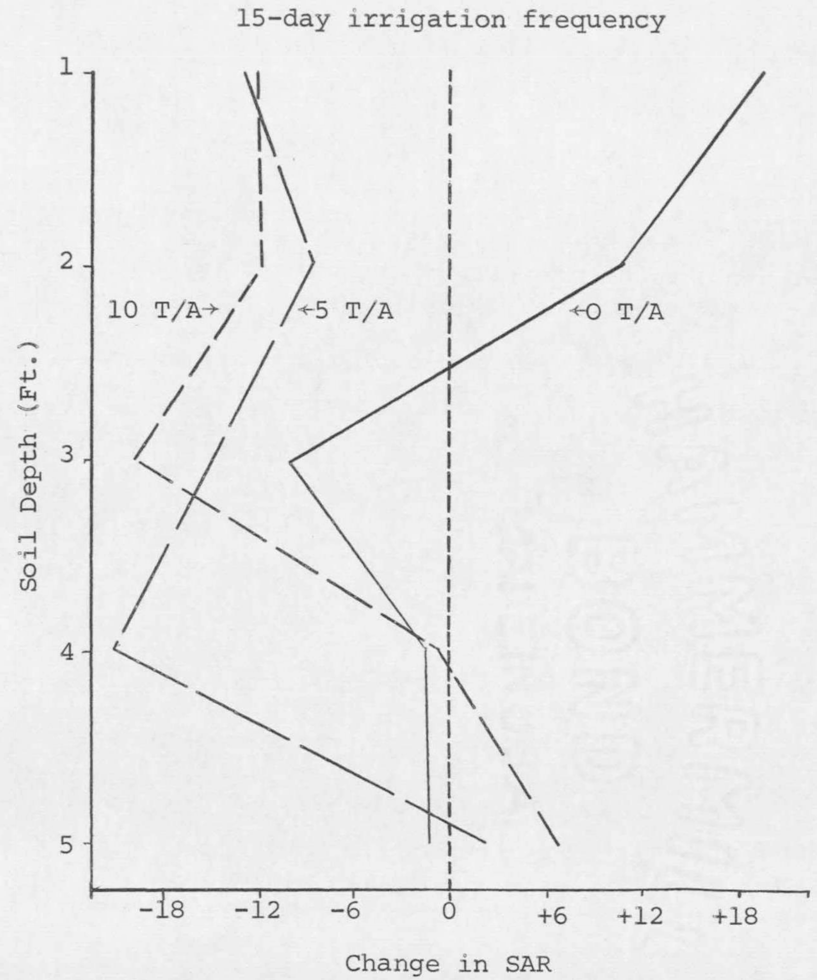


Figure 24c. The change in sodium-adsorption-ratio(SAR) with depth as a function in gypsum rates (0, 5 and 10 tons per acre) and irrigation frequency is described. The SAR is described at each depth as decreasing (negative) or increasing (positive).

become thinner and subsequently, led to a more flocculated state. The change from a dispersed system to a more flocculated one increased the capability of this saline-alkali soil to transmit water. The end result of this changing Na:Ca ratio is the greater ability of irrigation water to move through the soil profile and leach out excess salts. That this did occur is indicated by the following electrical conductivity data.

Electrical conductivity is a measurement used to evaluate the overall salt status of a soil sample. Table 22 presents electrical conductivity (EC) data which is graphed in Figures 25ab and 25c. As depicted in these diagrams, gypsum lowered the EC to a greater extent than plots without gypsum. This is attributable to the effect of gypsum on increasing the ability of the soil to conduct water, thereby, leaching out larger quantities of excess salt. Again, this held true within the crop rooting zones of 0-3 feet deep, whereas the depths four and five feet were zones of salt accumulation. A comparison of the irrigation frequencies and scale magnitudes of these figures indicate the 5-day frequency was most effective in reducing the EC. This is largely due to the greater volume of water infiltrated into the 5-day frequency plots as depicted in Table 23. It should be noted that evaporation is not accounted for in these data. As can be seen, the totals for the full summer of irrigation indicate the 5-day frequency infiltrated considerably more water, as would be

Table 22. Electrical conductivity(EC) data before and after irrigation treatments as a function of gypsum rates and irrigation frequency.

depth in feet	Gypsum rate tons per acre 0 before	0 after	0 ΔEC	5 before	5 after	5 ΔEC	10 before	10 after	10 ΔEC
5-day irrigation frequency									
1	16.1	14.2	-1.9	21.0	18.2	-2.8	20.2	15.1	-5.1
2	27.8	22.4	-5.4	30.6	25.4	-5.2	32.2	22.4	-9.8
3	18.9	17.0	-1.9	17.5	16.9	-0.6	21.6	20.6	-1.0
4	21.3	22.3	1.0	17.0	17.5	0.5	15.5	17.9	2.4
5	14.0	14.2	0.2	12.7	12.5	-0.2	12.2	11.3	0.8
10-day irrigation frequency									
1	15.8	17.3	1.5	22.8	20.5	-2.3	21.3	17.5	-3.8
2	19.1	20.2	1.1	21.2	15.4	-5.8	20.3	18.9	-1.4
3	18.4	17.3	-1.1	19.0	16.6	-2.4	24.1	22.4	-1.7
4	13.3	14.5	1.2	25.7	24.3	-1.4	14.5	15.2	0.7
5	18.1	15.2	-2.9	10.3	12.5	2.2	10.2	11.1	0.9
15-day irrigation frequency									
1	17.4	20.2	2.8	14.3	14.4	0.1	12.2	12.8	0.6
2	24.2	25.6	1.4	22.8	19.4	-3.4	15.6	13.2	-2.4
3	21.6	19.2	-2.4	22.8	16.3	-6.5	18.1	15.4	-2.7
4	15.4	14.3	-1.1	19.8	12.2	-7.6	19.3	20.2	0.9
5	13.2	14.3	1.1	15.8	11.5	-4.3	12.7	12.5	-0.2

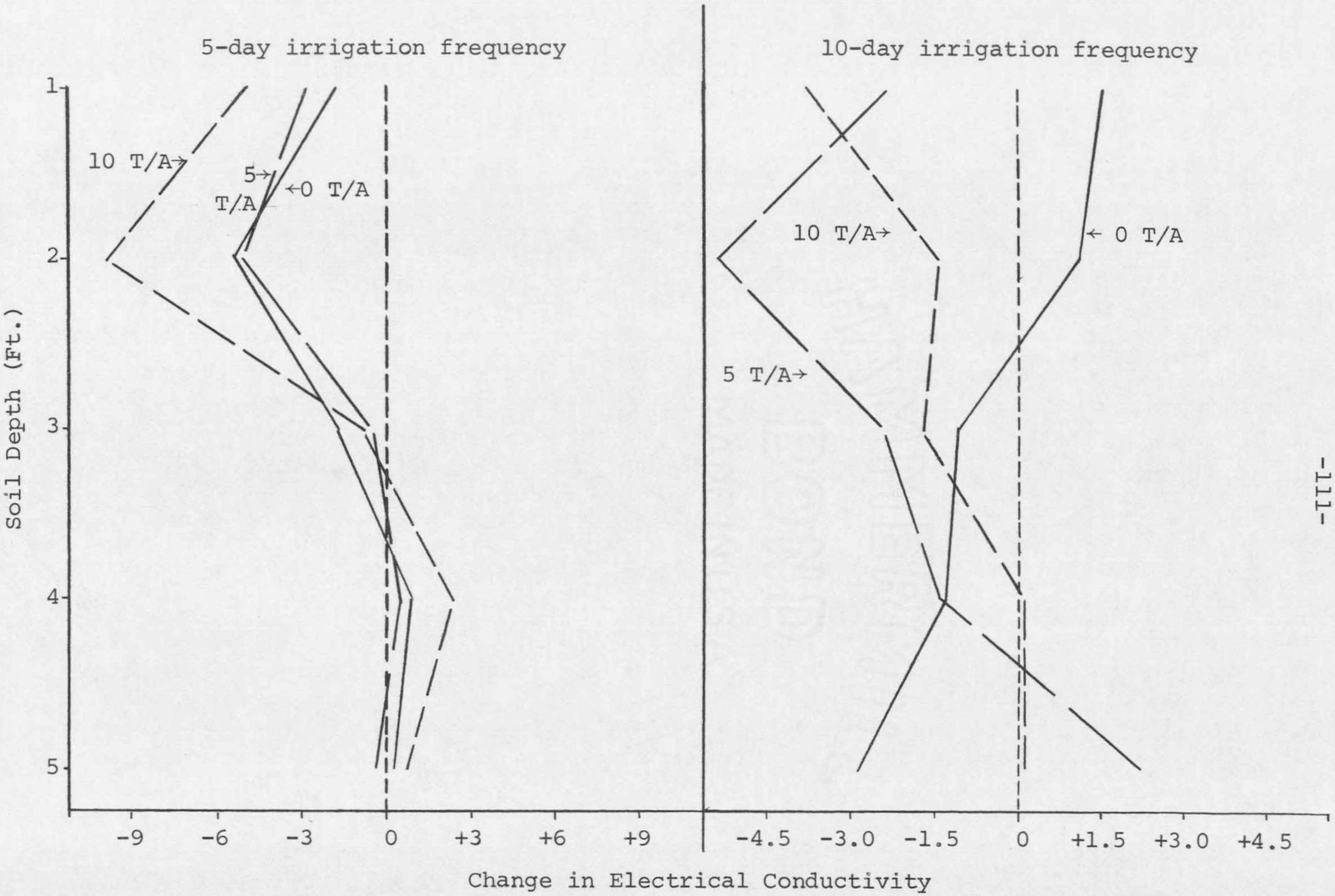


Figure 25ab. The change in electrical conductivity(EC) with depth as a function of gypsum rates (0, 5 and 10 tons per acre) and irrigation frequency is described. The EC is described at each depth as decreasing (negative) or increasing (positive).

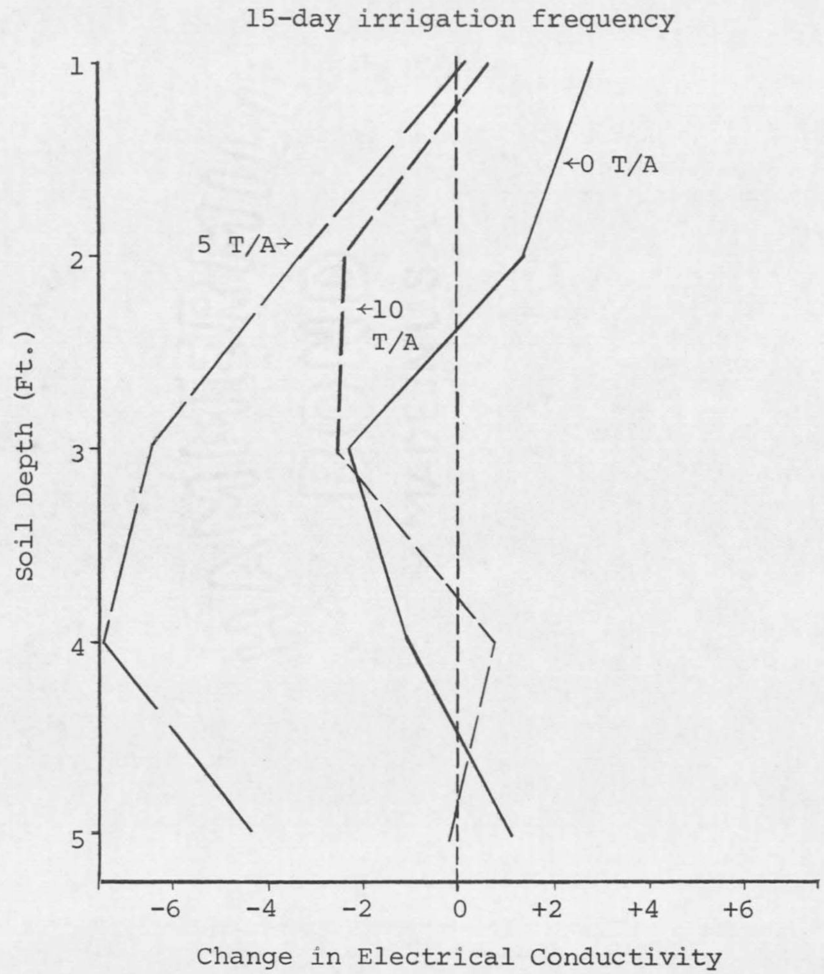


Figure 25c. The change in electrical conductivity(EC) with depth as a function of gypsum rates (0, 5 and 10 tons per acre) and irrigation frequency is described. The EC is described at each depth as decreasing (negative) or increasing (positive).

expected, and therefore, had more water available for leaching purposes. It follows, that the greater quantities of water added coupled with more frequent wetting-drying cycles (5-day frequency) and gypsum treatments was considerably more effective than the 10- and 15-day irrigation treatments in removing excess salts. In fact, the EC of the one foot zone for the 15-day frequency increased with the 0, 5 and 10 ton per acre gypsum treatments. This can be attributed to the long time between irrigations which resulted in a net upward movement of water and salts due to surface evaporation.

The ability to predict changes in the soil solution concentration in a rapid and comprehensive manner during infiltration and drainage was attempted by use of soil-water extraction tubes. These access tubes with porous cups on the end were at five soil depths from .5 to 4.5 feet, and by applying a suction to each tube a soil water extract from the respective soil depth was taken in a rapid manner right in the field. The technique was met with only partial success since water extracts were easily obtained from soil depths 2.5, 3.5 and 4.5 feet, but the depths near the surface, namely .5 and 1.5 feet, were generally too dry to extract a water sample by this technique, except immediately after irrigation. Time consuming attempts to get water extracts from the top, one-half of the profile only succeeded in decreasing the quantity of data from the lower one-half of the profile. Chemical analysis of these extracted samples are listed in Table 24.

Table 23. Water infiltration, as determined with parshall flumes, for each irrigation application is listed. The total water infiltration during the summer into each irrigation frequency is listed at the bottom. Evaporation is not accounted for in these data.

date	frequency (days)	infiltration (inches)
7-13	5	3.21
"	10	5.26
"	15	*
7-18	5	1.82
7-23	5	2.35
"	10	2.14
7-28	5	1.53
"	15	3.09
8-2	5	1.17
"	10	1.13
8-7	5	1.75
8-12	5	1.34
"	10	1.27
"	15	1.38

irrigation frequency	total infiltration (inches)
5-day	13.17
10-day	9.91
15-day	4.36*

* One infiltration value is missing for the 15-day irrigation frequency.

From these tables the sodium-adsorption-ratio (SAR) was calculated (Table 25) in order to observe the changes in sodium levels relative to the other cations. As can be seen by the SAR data, the same strong trends exist in these direct field extracts as were found in extracts determined in the laboratory from soil samplings. That is, gypsum in conjunction with the most frequent irrigation interval (5-day frequency) was the most effective treatment in reducing the SAR and leaching out excess salts in this saline and alkali soil.

Thus, the measured increase in soil hydraulic properties had the effect of removing large quantities of excess salts. But, one summer of gypsum and irrigation treatments did not reduce the saline-alkali status of this soil to acceptable levels for good crop growth. The literature states crop growth is retarded when the SAR is greater than 15 and the EC is greater than 4 mmhos/cm. A review of Tables 21, 22, 25a and 25b show about 99% of the SAR and EC values are above tolerable limits which renders this soil to be classed saline and alkali.

However, this soil has been forced out of its static unproductive state and placed on a route leading to reclamation and successful crop growth. The decreases in SAR and EC due to 10 tons of gypsum and the 5-day irrigation frequency implies another summer of such treatments could reduce these saline-alkali conditions to tolerable levels for crop production.

Table 24. Chemical analysis of samples from soil extracting tubes. Samples were taken on various dates during the gypsum and irrigation treatments.

date	depth in feet	NO_3-N	K	SO_4	Ca	Mg	Na	E.C.(mmhos/cm)
		parts per million						
5 day irrigation-10 ton treatment								
7-28	2.5	.3	45	5062	430	238	12750	35.5
8-22	2.5	.5	28	79	425	978	4800	26.2
7-29	3.5	2.4	45	3438	370	196	9000	27.0
8-22	3.5	2.8	45	101.3	435	1450	5675	21.0
7-28	4.5	3.8	22.5	4062	240	210	7700	28.0
8-22	4.5	2.4	45	90	270	1075	4800	27.5
5 day irrigation-5 ton treatment								
7-27	1.5	.7	108	126	270	938	7450	35.0
8-5	1.5	4.4	62	98	305	925	6225	31.0
7-28	2.5	5.9	22	1462	205	81	2110	14.0
8-5	2.5	8.0	22.5	34.5	240	405	2190	14.0
8-22	2.5	6.5	28	11	262	334	1825	12.0
7-28	3.5	0.0	22.5	1895	335	116	6525	16.5
8-5	3.5	.5	56	76	600	1406	2188	16.0
8-22	3.5	.5	22	30	305	590	2625	17.5
8-30	3.5		112		325	794	2425	
7-28	4.5	0.0	45	2225	270	143	2960	18.5
8-5	4.5	.2	22	40	250	750	3225	18.5
8-22	4.5	.5	22	33	280	708	2910	18.5
5 day irrigation-0 ton treatment								
7-28	3.5	0.0	45	2075	270	131	2735	18.0
8-8	3.5	.7	22	35	115	605	3350	18.5
8-26	3.5							19.9
7-28	4.5	0.0	45	2700	305	133	3685	22.0
8-4	4.5	.3	22	32	150	647	2850	17.0
8-26	4.5							16.0

(continued)

Table 24 (continued).

date	depth in feet	NO_3-N	K	SO_4	Ca	Mg	Na	E.C. (mmhos/cm)
		parts per million						
10 day irrigation-10 ton treatment								
8-7	1.5	9.5	22	96	210	1057	4825	29.0
8-19	1.5	13.1	22	120	335	1262	2375	23.0
7-27	2.5	0.0	1	1125	42	128	6625	29.7
8-7	2.5	1.6	22	88	335	1110	5150	25.0
8-28	2.5	.7	22	93	355	1075	5000	25.0
7-27	3.5	0.0	22	2150	335	128	2625	18.0
8-7	3.5	.2	22	51	370	633	2795	17.5
8-20	3.5	0.0	22	58	370	678	2950	17.5
7-27	4.5	0.0	22	2300	305	136	2850	18.5
8-7	4.5	1.0	22	63	325	735	3410	19.5
8-20	4.5	.2	22	52	335	678	2850	18.0
10 day irrigation-5 ton treatment								
8-20	1.5	11.0	22	30	305	892	5500	30.0
7-27	2.5	0.0	45	2150	335	118	3910	18.0
8-7	2.5	1.8	22	52	380	590	3285	19.0
8-21	2.5	.5	22	51	374	578	2960	17.5
8-31	2.5		62		370	590	3100	16.8
7-27	3.5	0.0	45	2375	270	148	4100	19.5
8-7	3.5	.7	22	59	270	812	3350	19.5
8-21	3.5	.3	22	59	305	790	3225	19.0
8-31	3.5		62		305	782	3100	18.1
7-27	4.5	0.0	45	1925	235	126	2735	17.0
8-7	4.5	0.0	22	46	280	590	2575	16.5
8-21	4.5	.2	22	47	270	605	2625	16.0
8-31	4.5		62		305	590	2475	15.6

(continued)

Table 24 (continued).

date	depth in feet	parts per million NO_3-N	K	SO_4	Ca	Mg	Na	E.C. (mmhos/cm)
10 day irrigation-0 ton treatment								
8-19	1.5	12.7	45	188	460	1958	10555	55.0
8-7	2.5	2.4	22	130	305	1468	7300	38.0
8-19	2.5	.3	22	130	180	691	4085	21.5
7-27	3.5	0.0	45	3950	370	213	8650	28.0
8-7	3.5	0.0	56	93	125	1306	5700	36.0
7-27	4.5	0.0	45	32375	305	188	355	24.0
8-7	4.5	0.0	45	68	150	907	4000	22.0
8-21	4.5	.2	45	58	240	858	3620	21.0
15 day irrigation-10 ton treatment								
8-1	3.5	.2	45	1600	305	85.7	2375	15.0
8-28	3.5		45		345	443	2325	15.1
8-1	4.5	.2	45	1925	240	110	2910	17.0
8-28	4.5		45		285	578	3225	17.8
15 day irrigation-5 ton treatment								
8-2	1.5	0.0	62	6750	370	658	14900	43.0
8-2	2.5	4.3	45	2375	205	134	6185	23.0
8-13	2.5	1.6	22	56	150	765	4175	20.5
8-28	2.5		156		212	1306	3062	
8-2	3.5	.2	45	2075	270	128	2850	18.0
8-29	3.5		78		300	773	3219	
7-23	4.5	0.0	45	2375	270	136	3025	20.0
8-2	4.5	.5	45	2075	270	131	2850	18.0
8-26	4.5		45		200	318	1575	16.4

(continued)

Table 24 (continued).

date	depth in feet	parts per million NO_3-N	K	SO_4	Ca	Mg	Na	E.C. mmhos/cm)
15 day irrigation -0 ton treatment								
8-4	2.5	2.4	62	.71	180	842	5350	28.0
8-30	2.5		156		112	1306	7125	
8-4	3.5	.45	59	24.5	790	4500		150.0
8-4	4.5	.3	22	41	150	735	4085	25.5
8-26	4.5		62		110	691	3520	18.3

Table 25. Sodium-adsorption-ratio (SAR) data from soil moisture extracting tubes at various dates and depths.

depth in feet	sampling date	gypsum rate T/A	SAR
5-day irrigation frequency			
2.5	7-28	10	122.6
2.5	8-22	10	29.3
3.5	7-29	10	94.3
3.5	8-22	10	29.4
4.5	7-28	10	87.4
4.5	8-22	10	29.3
1.5	7-27	5	48.1
1.5	8-5	5	40.1
2.5	7-28	5	31.6
2.5	8-5	5	20.0
2.5	8-22	5	17.6
3.5	7-28	5	78.4
3.5	8-5	5	11.2
3.5	8-22	5	20.2
3.5	8-30	5	16.5
4.5	7-28	5	36.2
4.5	8-5	5	23.1
4.5	8-22	5	21.1
3.5	7-28	0	34.2
3.5	8-8	0	27.7
3.5	8-26	0	*
4.5	7-28	0	44.4
4.5	8-4	0	22.5
10-day irrigation frequency			
1.5	8-7	10	30.1
1.5	8-19	10	13.3
2.5	7-27	10	114.8
2.5	8-28	10	31.5
2.5	8-28	10	29.9
3.5	7-27	10	30.9
3.5	8-7	10	20.5
3.5	8-20	10	21.1
4.5	7-27	10	34.1
4.5	8-7	10	24.0
4.5	8-20	10	20.6
1.5	8-20	5	36.0
2.5	7-27	5	46.8
2.5	8-7	5	24.6
2.5	8-21	5	22.4
2.5	8-31	5	23.6
3.5	7-27	5	49.8
3.5	8-7	5	23.0
3.5	8-21	5	22.2
3.5	8-31	5	21.4
4.5	7-27	5	35.8
4.5	8-7	5	20.0
4.5	8-21	5	20.3
4.5	8-31	5	19.1

(continued)

Table 25. (continued)

depth in feet	sampling date	gypsum rate T/A	SAR	depth in feet	sampling date	gypsum rate T/A	SAR
(continued) 10-day irrigation frequency				15-day irrigation frequency			
1.5	8-19	0	47.8	3.5	8-1	10	31.0
				3.5	8-28	10	19.6
2.5	8-7	0	38.5				
2.5	8-19	0	31.0	4.5	8-1	10	39.0
				4.5	8-28	10	25.3
3.5	7-27	0	88.7				
3.5	8-7	0	32.9	1.5	8-2	5	107.6
4.5	7-27	0	4.0	2.5	8-2	5	82.5
4.5	8-7	0	27.2	2.5	8-13	5	30.6
4.5	8-21	0	24.5	2.5	8-28	5	17.3
				3.5	8-2	5	35.8
				3.5	8-29	5	22.4
				4.5	7-23	5	37.5
				4.5	8-2	5	35.6
				4.5	8-26	5	16.1
				2.5	8-4	0	37.2
				2.5	8-30	0	41.2
				4.5	8-4	0	30.5
				4.5	8-26	0	27.4

SUMMARY AND CONCLUSIONS

The effects of gypsum rates (0-5-10 T/A) and irrigation frequency (5-10-15 days) on soil physical and chemical properties of a saline-alkali soil were evaluated.

The effects of the above treatments on soil crusting properties were studied. Preliminary laboratory tests indicated treatment of the field soil with gypsum rates (0-5-10-20 T/A) significantly reduced crust strength. Subsequent analysis of gypsum treatments in the field before and after a summer of irrigation were made. Before irrigation gypsum significantly reduced crust strength within the surface two inches, and the 5 T/A rate was equally effective as the 10 T/A rate. After irrigation over the gypsum, crust strength was significantly reduced to a tested depth of six inches, and the 10 T/A rate was significantly more effective than the 5 T/A rate. Also, irrigation had the effect of significantly reducing crust strength which was attributed to the leaching out of salts resulting in a decreased SAR as indicated by chemical analysis data. No significant differences were present between irrigation frequencies but definite trends in the data indicated the 5-day frequency was most effective in decreasing soil crust strength with the 15-day frequency the least effective.

The change in the swell-shrink factor of this saline-alkali soil due to treatments was evaluated. Although shrinking was decreased with treatments, no significant differences were present. However, trends in the data demonstrated the swelling-shrinking ability of this soil was decreased most effectively by the 5-day irrigation frequency in conjunction with gypsum treatments, which was attributed to the replacement of Na by Ca on the soil exchange complex.

The rate of infiltration and quantity of water moving through the surface six inches as a function of treatments was evaluated. These data indicated gypsum increased the ability of the surface soil to transmit water, and a greater quantity of water was moving through the gypsum treated soil. This had the effect of increasing leaching efficiency. The 10 T/A rate was consistently more effective than the 5 T/A rate.

Preliminary laboratory measurements on hydraulic conductivity and water flux were made utilizing irrigation water on undisturbed soil cores from the experimental site. When a saturated gypsum solution was substituted for the irrigation water the hydraulic properties of the soil cores were increased by as much as 246% at soil-water tensions observed in the field.

Hydraulic conductivity (K) and water flux (Q) were calculated within the undisturbed saline-alkali soil profile at various times during irrigation and drainage. These data indicated gypsum consistently increased the hydraulic properties of the profile and the 10 T/A rate appeared to be more effective than the 5 T/A rate. A relationship was present where the K and Q differences between gypsum and no gypsum was of a decreasing magnitude with more frequent irrigation applications. This was attributed to the greater removal of salts by the 5-day- in comparison to the 15-day irrigation frequency in both the gypsum and non-gypsum treated plots. Thus, the heavier irrigation application tended to make the effects of gypsum less apparent.

Soil chemical analysis data indicated the measured increases in soil hydraulic properties had the effect of removing large quantities of excess salts, but one summer of gypsum and irrigation treatments did not reduce the extremely high saline-alkali status of this soil to acceptable levels for good crop growth. However, this saline-alkali soil was forced out of its static unproductive state and placed on a route leading to reclamation and successful crop production. The decreases in SAR and EC due to 10 T/A gypsum and the 5-day irrigation frequency implies another summer of such treatments could reduce the saline-alkali condition to tolerable levels for good crop production.

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