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 co-efficients 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)

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

and

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

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 <u>et al</u>. (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.

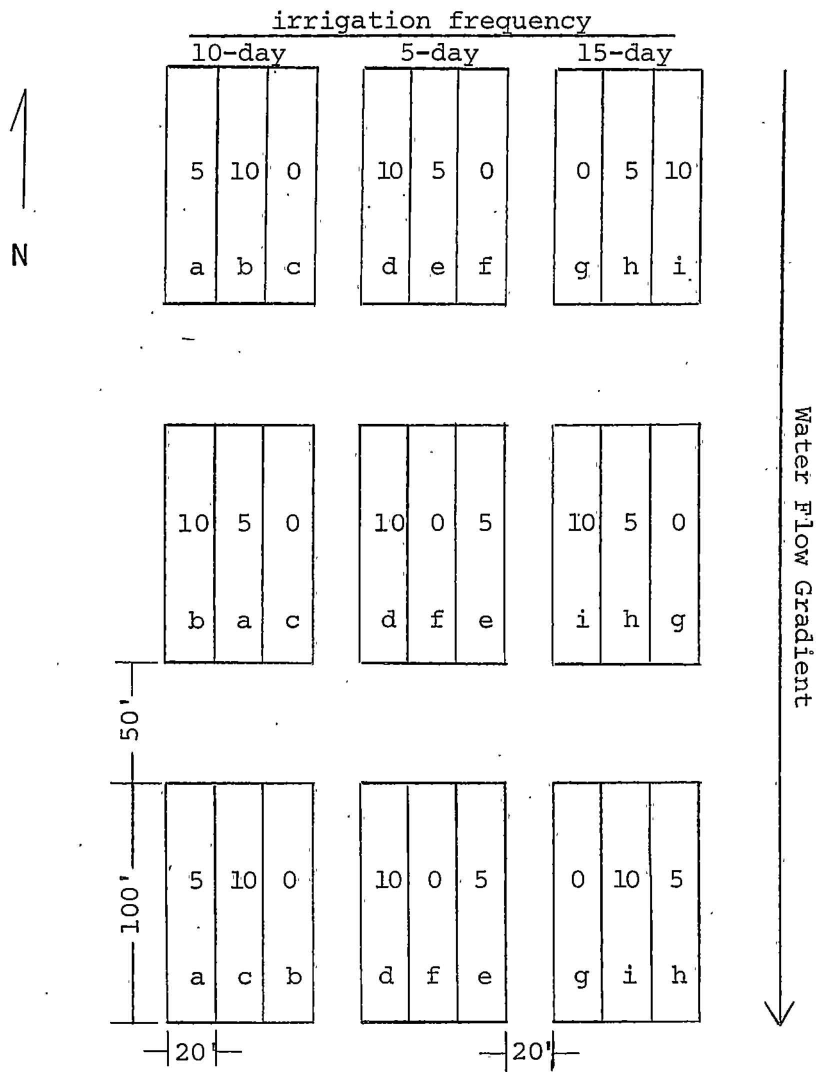

Figure 1. Field plot diagram of gypsum amendment and irrigation frequency study for reclamation of saline and alkali soil. The numbers within the plots designate gypsum rate in tons per acre, while the letters designate plot replication.

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:

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

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