Management of irrigation and drainage systems for salt balance: a solute transport study for saline and waterlogged soils

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A solute transport study for saline and waterlogged soils

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ABSTRACT

A study was conducted to evaluate the effects of sodium chloride (NaCl) and calcium chloride (CaCl₂) at different concentrations in the soil profile on saturated hydraulic conductivity, salt movement, and transport of nitrate-nitrogen (NO₃-N) and atrazine to the groundwater. Also, the effects of various water table depths were evaluated on salt movement and the fate of NO₃-N under simultaneous irrigation and drainage practices.

Two sets of experiments were conducted in the laboratory under simulated saline and waterlogged conditions. Three sets of (45, 75, and 115-cm long) soil columns were fabricated using PVC pipes of 20-cm diameter for this study. Large columns (115-cm long) were filled with a sandy loam soil brought from the bank of Squaw Creek river near Ames, Iowa. For one experiment, these long columns were filled with soil in seven layers of different bulk densities. For other four experiments, the soil was filled in the columns uniformly by mixing the entire soil profile to give a single bulk density for the entire column.

For the short columns, two types of soils were used (sandy loam soil from Squaw Creek and the nicollet loam soil from Iowa State University Farm at Ankeny, Iowa to pack the columns. These soils were packed in the columns at uniform bulk densities of 1.40 and 1.25 g/cm³ for sandy loam and nicollet loam soils, respectively.
The salt equilibria were obtained by mixing weighed amounts of salts in the weighed amounts of soil, and by subsequent saturating the soil in the columns with desired salt concentrations. Four levels of salt concentrations (3200, 6400, 19,200, and 38,400 ppm) were used for different experiments.

The results of this study showed that hydraulic conductivity of the soil decreased with the increase in salt concentrations. But reverse effect of salt concentrations was observed when salt concentrations were increased six-fold. The NO₃-N and atrazine leaching increased with increase in salt concentrations. The overall results of this study indicate that the simultaneous irrigation and drainage practices could be managed for soil reclamation by applying about 25 percent more water for irrigations. Also, nitrogen fertilizers can be managed better if proper irrigation and drainage systems can be designed for the benefits of the farmers by using some of the results of this study.
GENERAL INTRODUCTION

The world population in the year 2000 is likely to be about 6500 million, an increase of 72 percent in the population since mid 1972. The corresponding increase in the population of Asia, Africa, and Latin America, taken together, would be 86 percent in the same period (Mulk, 1992). As the problem of over population continues to outstrip food production in many countries, the need for major expansion of irrigation and drainage facilities becomes critically important. Because of shortage of arable lands, it would be essential to expand irrigation and drainage systems on marginal lands throughout the world for producing enough food to feed the growing population. This is a formidable challenge and an appropriate responsive solution would have to be found (Mulk, 1992).

The Council for Agricultural Science and Technology (1988) reported that some irrigation was practiced nearly 2,000 years ago in the southwestern states, but extensive irrigation has been practiced in the United States for one and a half centuries. In contrast, irrigation has been practiced for 9,000 years along the Nile, for 6,000 years along the Tigris and Euphrates rivers, and for 4,500 to 5,000 years along the Indus river in the Indian subcontinent and Yellow river in China. Worldwide, irrigated land expanded rapidly after 1950 increasing from about 92 million hectares to about 175 million hectares in 1972, an expansion rate of 3 percent per year leading to about 220 million hectares in 1984. The current rate of expansion is less than one percent per year (Higgins et al., 1987) due to limited availability of land and water
resources. Similarly, the area of irrigated land in the United States has essentially stabilized because of low commodity prices and limited water supplies.

According to some estimates half of the irrigated land needs either improvement or drainage to control salinity and waterlogging in arid and semi-arid areas of the world (Mulk, 1992). There is a rather growing need to concentrate more effort on the improvement of drainage in developing countries. According to an estimate, about 1.0 to 1.5 million hectares of land are being damaged each year around the world through man-induced salinization. The World's irrigated area has increased more than three-fold since 1950 (Schultz, 1992). Salinization is only one of the many problems that needs attention to correct our agriculture related problems.

Waterlogging is the primary source of salinization problems that can occur in arid and semi-arid climates. Drainage needs of tropical and temperate humid area lands are critical for agricultural sustainability and efficient productivity. In most countries, improved living standards can be achieved and sustained only if the agricultural sector develops rapidly. Hence, the need for a more rational and efficient use of land, water, and chemicals must be emphasized.

New and expanding water issues are creating increasing demands for alternative and innovative solutions to complex water supply and water quality problems. These issues involve, limited water supplies accompanied by increasing water demand, and increasing public concern on water quality and environmental degradation issues.

Salinity and drainage problems have plagued agriculture in California, USA from the time irrigation was introduced in the second half of 19th century (Kelley and Nyei,
Similarly, salinization and waterlogging of agricultural land are major problems for irrigated agriculture in many arid and semi-arid regions of the world. For example, in Egypt, Pakistan, and India about 0.8, 6.0, and 10.7 million hectares, respectively have been affected by salinity (Carruthers and Smith, 1990). According to FAO and UNESCO estimates, about 125 million hectares of irrigated land (one-half of all existing irrigated systems) are seriously affected by salinity and waterlogging (Rhoades and Loveday, 1990). Accordingly, many salinity control and reclamation projects would be implemented in the near future, because drainage systems can often reclaim saline lands and prevent future salinization. One important parameter for these systems is the optional groundwater table depth which should prevent salinity after installation of drainage system (Spijkers and Hendrickx, 1991).

Where sufficient good quality irrigation and rain water is available for leaching of the soil profile, salinization can be prevented by the installation of drainage systems which discharge excess water and salts. Under these circumstances the exact depth of the ground-water table is of minor importance and can be quite shallow (Spijkers and Hendrickx, 1991).

Low levels of precipitation accompanied by exceedingly high rate of evapotranspiration in arid and semi-arid regions cause and aggravate the salinity problems. Therefore, all-out efforts are being made not only to exploit the conventional sources of water but also to develop non-conventional methods and introduce technologies and water management techniques which promote crop production per unit of water consumed (Shankar and Pillai, 1990) and prevent the accumulation and
occurrence of various soluble salts in soil or water in concentrations that interfere with the growth of plants. In high concentrations these salts may reduce crop productivity. Soils usually contain naturally occurring salts, and more dissolved salts arrive with irrigation water under irrigated conditions. Since plants absorb nearly pure water, the dissolved salts remain behind in the soil after evapotranspiration. As the salts buildup, plant growth is affected and yields decline. The major salts include chlorides, sulfates, and bicarbonates of sodium, magnesium, and potassium (California Agriculture, October, 1984). An electrical conductivity measurement of the soil solution is a reliable estimate of soil salinity. A saline soil is one with an EC of 4 mmhos/cm (2500 ppm) or more in the saturated extract. Crops vary in flooding tolerance or susceptibility to salts.

Drainage is needed to provide a suitable environment for plant growth during the growing season. But at the same time excessive drainage is undesirable as it reduces soil water available to growing plants and leaches fertilizers and pesticides carrying them to receiving streams and to deeper groundwater systems where they act as pollutants (Kanwar et al., 1991). The drainage problems of an irrigated area are closely related to its transmitting properties. Generally, in arid and semi-arid regions where the natural subsurface drainage is not well developed, canal irrigation has resulted in the rise of water tables. When the groundwater table level rises close to the ground surface, salinization and waterlogging conditions occur. This requires the undertaking of detailed water balance studies (Singh and Singh, 1982). Various components of the water balance equation, subsurface inflow-outflow, recharge from
rainfall and/or irrigation, loss of water through capillary rise, evapotranspiration, groundwater pumpage and seepage from irrigation system need to be estimated.

The salinity and waterlogging are interrelated problems that need to be studied systematically. Numerous studies have been conducted in the past, and still much work needs to be done to thoroughly understand the solute transport and water table management under salinity conditions. Also, soil and water pollutants need to be studied under saline and waterlogged conditions, which unfortunately have not been given much attention in the past as is clear from the available literature.

Research is needed to understand the behavior of solute transport, hydraulic conductivity, use and loss of nitrogen and pesticides with drainage water, and the role of water table management practices on the management of salinity control. These areas of research need are the motivation for this study, which includes a comprehensive laboratory data collection work on large disturbed soil columns under thoroughly replicated tests.

Objectives

With the aim of developing a better understanding of the management of irrigation and drainage systems for salinity control, this study was conducted with the following specific objectives:

1. To determine the effects of two salts (NaCl and CaCl₂) on saturated hydraulic conductivity of a layered and a uniformly packed soil in columns under laboratory conditions.
2. To investigate the effects of salts on the movement of nitrate and atrazine through the soil profile using large columns.

3. To develop techniques for the optimization of irrigation and drainage practices for salinity control by using the concepts of water table management and the data collected from objectives (1) and (2).

Dissertation format

This dissertation embodies the candidate's original research work on the management of irrigation-drainage systems for salt balance – solute transport in saline and waterlogged soils. The dissertation contains six separate papers. Each paper was written by the author in a format acceptable for publication in technical journals.

The first and fifth papers were presented at the 1993 Mid-Central Meeting of the American Society of Agricultural Engineers, St. Joseph, Missouri. In the meantime, all these six papers will be submitted for publication to appropriate journals. Each paper in this dissertation contains an abstract, introduction, materials and methods, results and discussion, conclusions, and references. The papers are preceded by a general introduction and review of literature and followed by a general summary. The references for the general introduction and review of literature follow the general summary.
Salinity effects on crops

Maas (1986) reviewed salt tolerance of plants in detail. He reported that salt tolerance of plants not only varies considerably among species but also depends heavily on the cultural conditions under which the crops are grown. Many plant, soil, water, and environmental factors interact to influence the salt tolerance of a plant. He has given a comprehensive list of almost all crops grown in the world for their salt tolerance. As a reference, few major crops selected from Maas (1986) list are referred for salinity levels on the basis of electrical conductivity (EC). Corn, cotton, rice, soybean, sugarcane, and wheat can grow safely at EC levels of 1.7, 7.7, 3.0 (submerged in water), 5.0, 1.7 (submerged), and 6.0 mmhos/cm, respectively. But to obtain an estimated 50 percent of the potential yield of cotton, wheat, corn, and rice can be grown at EC of 17, 13, 5.9, and 3.6 mmhos/cm (submerged), respectively, and with 50 percent emergence, cotton wheat, corn, and rice can grow at EC 15, 14-16, 21-24, and 18 mmhos/cm, respectively.

It is difficult to review all crops for their salt tolerance, but a few crop studies have been reviewed in support of salinity studies.

Bernstein and Hayward (1958) found that Na dispersed soils reduce air and water permeability and form a barrier to root penetration and seedling emergence. According to them sodium soils become hard and sticky.
Gupta et al. (1961) reported that poor root penetration occurs in Na\(^+\) soils and nutrients are not taken up by the crop, slowing growth of plants. Also in sodic soils excessive cloddiness and hardpan occur in high pH range. They further investigated that crops require 25 percent more nitrogen for potential growth compared to neutral soils.

Abou-el-Fadl et al. (1974) investigated effects of NaCl+CaCl\(_2\) salts applied in equal weights at 1,000, 2,000, and 3,000 mg/L to soils. They found that increasing level of salinity in irrigation water decreased the vegetative growth and seed yield of both dill and black cumin plants loosing 78 percent of the value in dill oil due to salinity level of 3,000 mg/L.

Chakraborty et al. (1980) reported that increase in salinity and application of irrigation water reduced growth of corn and resulted in chlorotic leaf symptoms. However, the application of water to the saline soil increased the use of different plant nutrients.

Kishore et al. (1983) tested different varieties of egg plant for salt tolerance in artificially salinized soils at 0, 4, 6, 8, and 10, mmhos/cm ECe, and found that in saline soils above the EC of 4 mmohs/cm in the root zone ultimately affected the flowering and fruiting behavior of the plant.

Lubach and Bodman (1983) determined that high to extreme salinity hazard is between 700 and 1300 ppm chlorides, medium between 350 and 700 ppm chlorides, and low less than 350 ppm chlorides. They reported that if excessive quantities of salts accumulate in the root zone, the crop has difficulty in extracting enough water.
Francois et al. (1986) studied salinity effects on semi-dwarf and durum wheat crops. They used NaCl and CaCl₂ salts (1:1 by weight) and maintained EC values of 1.5, 2.5, 5.0, 7.4, 9.9, and 12.4 mmhos/cm for first year and 1.5, 4.0, 8.0, 12.0, 16.1, and 20.5 mmhos/cm the second year. Relative grain yields of one semi-dwarf wheat and two durum cultivars were unaffected by soil salinity up to 8.6 and 5.9 mmhos/cm. Each unit increase in salinity above threshold reduced yield of the semi-dwarf cultivar by 3 percent and the two durum cultivars by 3.8 percent.

Mangal et al. (1987) studied certain leafy vegetable crops for their salt tolerance capacity in artificially salinized soils of EC values of 0, 2.5, 7.5, 10.0 and 12.5 mmhos/cm and found that vegetative growth, fruit, and seed germination were declined sharply under higher salinity levels. The reduction in germination, growth and seed yield was directly related to increased levels of salinity.

Krishnamurthy et al. (1987) studied effect of NaCl toxicity on chlorophyll breakdown in nine varieties of rice and found that the NaCl treatment increased the chlorophyll content up to four weeks at salinity level of 10 mmhos/cm.

Mangal et al. (1988) worked on the salt tolerance of melon in artificially salinized soil with NaCl and CaCl₂. Percentage germination and melon yield of all cultivars decreased linearly with increasing soil salinity. If soil salinity exceeded 1.11 mmhos/cm, mean germination decreased at a rate of 9 percent per unit increase in soil salinity. Similarly, the yield decreased at a rate of 8.73 percent for each unit of EC exceeding 1.03 mmhos/cm. The maximum salt tolerance limit, they found, was
associated with soil ECe value of about 5.20 to 6.32 mmhos/cm.

Raghuwanshi et al. (1987) conducted experiment on linseed crops grown on a sodic soil (ESP 30) with N-Fertilization of 60 kg/ha and 6-7 irrigations of 5 cm each. They reported that the fertilization and irrigation practices differ remarkably in view of adversely altered physico-chemical nature of the soil, and release of moisture.

Singh et al. (1987) in their literature review found that the response of plants to nitrogen and phosphorus in salt affected soils in well documented and concluded that plant nutrients are affected by salinity conditions.

Council for Agricultural Science and Technology (1988) reported that all irrigation waters contain some dissolved salts, which become more concentrated in the soil because ET uses essentially pure water leaving the salts in the remaining soil water. It suggests to prevent yield reduction or salt damage to crop by applying some water in excess of that required for ET so that accumulated salts be leached below the root zone. The leaching requirement depends on the salt concentration in the irrigation water or soil and the sensitivity of the crop to salinity.

Council for Agricultural Science and Technology (1988) reported that at a given salinity level of applied water, corn yield decreases as salinity levels increase. Increasing the amount of applied water increases yields because of greater leaching of salts from the root zone.

Francois et al. (1988) studied salinity effects on triticale cultivars grown on different soils using NaCl and CaCl2 (1:1 by weight) in six EC values of 1.8, 2.6, 5.1, 7.5, 9.6, and 12.3 mmhos/cm the first year, and 1.4, 3.9, 7.9, 12.0, 16.0, and 20.3
mmhos/cm the second year. Relative grain yield was unaffected by soil salinity up to 7.3 mmhos/cm (ECe in the root zone). Each unit increase in salinity above 7.3 mmhos/cm reduced grain yield by 2.8 percent.

Fowler et al. (1988) observed a variable response to salinity among the stages of plant development. The Russian - Thistle was less salt tolerant during germination than at later stages. Germination and yield declined linearly with increasing salinity.

Gill (1988) reported that saline water irrigation at vegetative growth caused severe reduction in grain (100%) and straw yield (59.4%) of millet at EC level $> 10.6$ mmhos/cm.

Qadar (1988) studied 71 genotypes of rice, only 18 could produce more than 50 percent grain at pH 9.8 compared with pH 8.5.

Singh et al. (1988a) studied the effect of exchangeable sodium percentage of 87, 62, 44, 34, and 27 on growth, yield and chemical composition of brassica. They found that increasing ESP decreased N, P, K, Ca, Mg, Fe, Zn, Cu and Mn concentrations and decreased that of Na$^+$ in seed and stover and these crops can be grown successfully up to about 44 ESP without a significant reduction in yield.

Singh et al. (1988b) studied the effect of exchangeable sodium percentages of 86, 61, 43, 33, and 28 on forage yield and chemical composition of millet under field conditions. They found that increasing ESP decreased the yield and contribution of Ca$^{++}$, K, and P but increased that of Na$^+$ in the plants.

After review of salt tolerance of crops, it was decided to study salt treatments of 3,200 ppm and 6,400 ppm (EC 5 and 10 mmhos/cm) at which most of crops could
be grown to a certain degree of success. Also salt concentrations of 19,200 and 38,400 ppm were studied for leaching of salts by percolating fresh water and saline water. Solute transport studies were conducted at the extreme conductivity levels of 30 and 60 mmhos/cm to examine the salt effects on nitrate and atrazine movements through soil profile.

**Soil characteristics and solute transport**

Bodman and Fireman (1950) have shown that satisfactory permeability can be maintained with a soil, which is 30 percent saturated with sodium, by using a high electrolyte concentration. They did not investigate the region between the initial high salt concentration and distilled water, the use of which resulted in drastic reduction in permeability.

Fireman (1944) working with sandy loam obtained a high and constant permeability when 800 ppm CaCl₂ solution was used as the percolating liquid. When distilled water was used the permeability decreased in a period of 5 hours to less than one-hundredth of that obtained with the CaCl₂ solution. A NaCl solution containing 4500 ppm, with this soil, caused a continuous decrease in permeability, but for the period of experiment the rate of flow was always higher than that obtained with distilled water.

Gardner (1945) studied the effect of sodium and calcium on soil dispersion and settling volume. He found that calcium soils consist normally of comparatively dense
microaggregates that settle rapidly from suspension, whereas soils dispersed after treatment with solutions containing high percentages of sodium from massive aggregates of low density that settle slowly, occupying a large volume.

Gardner (1945), Martin and Richards (1959), and Reeve, (1960) have provided a qualitative understanding of the hydraulic conductivity changes accompanying the percolation of salt solutions through soils. The presence of divalent ions such as calcium generally stabilizes or increases hydraulic conductivity, while the presence of sodium in the percolating solution or on the ion-exchange complex frequently decreases hydraulic conductivity, particularly at low salt concentrations. Relatively little is known about the quantitative effects of different salt solutions on soil hydraulic conductivity.

Christiansen (1947) was of the opinion that the use of water of very low electrolyte content could result in soil sealing to such an extent that reclamation of alkali soils would not be possible.

Quirk (1953) found that soil having high exchangeable sodium percentages will remain fairly permeable to waters of high electrolyte concentration on montmorillonites.

The U.S. Salinity Laboratory Staff (1954) proposed the term Sodium Adsorption Ratio (SAR), which is an approximate expression for the relative activity of Na⁺ ions in exchange reactions in soils. The soil solution cationic composition in SAR terms is commonly used to describe the cationic composition effect on soil hydraulic conductivity.
Quirk and Schofield (1955) worked on artificially packed pads (1-cm thick, 5-cm diameter) of soil from Rothamsted fields and were saturated with a given cation by leaching with a strong chloride solution of the ion for 12 hours. After this time a constant rate of flow was established. They conducted a series of successive studies with more dilute solutions, and measured the permeability at regular time intervals for a period of 5 hours. They observed decreases in permeability below a certain concentration. They obtained threshold concentrations of $2.5 \times 10^{-1} \text{M NaCl}$, $6.6 \times 10^{-2} \text{M KCl}$, $1 \times 10^{-3} \text{ M MgCl}_2$, and $3 \times 10^{-4} \text{M CaCl}_2$ when the soils were saturated with the appropriate cation.

Quirk (1957) showed that the hydraulic conductivity increases as the SAR, or associated Exchangeable Sodium Percentage (ESP), decreases and the solution concentration increases. They found it true as long as SAR had a value of at least 10, but for lower values of SAR the effect of electrolyte concentration on soil hydraulic conductivity was negligibly small.

Bernstein and Hayward (1958) and Gupta et al. (1961) reported that irrigation water high in Na⁺ has the ability to change the structure of soils with reasonable clay contents.

Gardner et al. (1959) have reported that in low sodium soil, the weighted mean soil water diffusivity was no more than doubled as the solution concentration was increased from 2 to 100 meq/liter, whereas in high sodium soils diffusivities changed by a few orders of magnitude at similar changes of salt concentrations. Also, Quirk and Schofield (1955) showed similar results for ranges of concentration commonly
encountered in soils. Effect of solution concentration on soil permeability in soil with divalent cations was negligibly small compared to monovalent soil systems.

Longnecker (1959) examined the relation between the SAR of irrigation water and ESP for several Texas soils and they found little correlation between the two. He attributed this to a lack of equilibrium between the soils and the irrigation water.

Reeve and Bower (1960) suggested that reclamation of sodic soils should start with high salt concentration water to increase permeability and facilitate leaching because of the fact that high electrolyte concentration affects soil permeability in sodic soils.

Fink and Thomas (1964), Foster et al. (1955), and Norish (1954) have shown that sodium saturated montmorillonites expand indefinite amounts in distilled water due to the imbibition of water into the interlayer space. Calcium saturated montmorillonites imbibe only about three layers of water in the interlayer space, thereby restricting expansion.

Posner and Quirk (1964) measured the swelling of montmorillonite saturated with monovalent and divalent ions in the presence of salt solutions. They found that sodium saturated montmorillonite exhibited extensive swelling at concentrations below 0.3 molal.

McNeal and Coleman (1966) found that increasing the SAR and decreasing the electrolyte concentration of the percolation solution induced a decrease in soil permeability. Such changes were more pronounced in soils containing expandable 2:1 layer silicates, especially, montmorillonite clays, than in soils containing kaolinite or
McNeal et al. (1966) found a good correlation between soil swelling, expandable clay content, and the hydraulic conductivity sensitivity which reflected the importance of the montmorillonite group as responsible for the reduction in permeability. However, the reduction in hydraulic conductivity occurred also at low ESP values, where no appreciable swelling was observed. They suggested that the reduction in permeability was due to clogging of conducting pores either by in situ mineral swelling or by migration of clay platelets which accumulated and decreased pore sizes.

McNeal et al. (1968) used a group of soils having variable clay content but nearly uniform clay-fraction mineralogy, the relative hydraulic conductivity in the presence of mixed-salt solutions decreased markedly with increasing clay content, particularly, at the lowest salt concentrations employed the stability of soils under high-sodium, low-salt conditions was greatly reduced by partial removal of the free iron-oxides. Replacing the Ca\(^{++}\) in percolating NaCl-CaCl\(_2\) solutions with Mg, measurably decreased soil hydraulic conductivity, although the effect was often negligible when comparisons were made at equivalent exchangeable sodium percentages.

Thomas and Yaron (1968) stated that under field conditions where a non sodic soil is irrigated with sodic water, a constant exchangeable content along the soil profile is difficult to achieve. Therefore, the transitional series of values determined by the volume of a specific water passed through a specific soil column must be taken into consideration. The continuous change in the flow rate of the solution during the
period between the first addition of sodic water and the achievement of equilibrium suggests that hydraulic conductivity measurements made at equilibrium are not particularly valuable for field prediction.

Thomas and Yaron (1968) conducted hydraulic conductivity experiments on four types of soil. The percolating solution they used, had a constant SAR and total electrolyte concentrations of 11 meq/L and 33 meq/L, respectively. The influence of the total electrolyte concentration of the solution and type of soil on the hydraulic conductivity can be seen. The effect of SAR on soil hydraulic conductivity is also important. They found decrease of soil hydraulic conductivity when three solutions with constant total (11 meq/L) and three SAR values 7.5, 14.0, 28.0 were passed through columns. At equilibrium, and SAR value of 7.5 corresponded to a decrease of soil hydraulic conductivity of 15%, while an SAR value of 28 reduced the initial hydraulic conductivity be 84 percent. These authors have also found that the soil hydraulic conductivity became constant only when a constant ESP was achieved along the soil column.

Thomas and Yaron (1968) concluded that when sodium containing water first flows through soil columns the relationship between the SAR of water and ESP of soil does not give a significant correlation, except at the surface. The total electrolyte concentration of the sodic water influenced the rate of sodium adsorption but at equilibrium the ESP in the soil column was influenced more by soil mineralogy and the cationic composition of water than by the total electrolyte concentration. Soils containing both mica and montmorillonite had a higher affinity for Na⁺ than did the
montmorillonitic soils. The continuous change in the soil hydraulic conductivity until a constant Na$^+$ percentage was achieved along the soil column makes it difficult to predict the flow of water in field conditions from equilibrium hydraulic conductivity.

Kramer (1969) reported that soil structure, porosity, and texture are critical factors in soil water movement and retention. Because clays furnish most of the internal surface of a soil and because of their colloidal properties, the clay fraction controls the most important soil properties.

Naghshineh-Pour et al. (1970) reported that SAR, ESP, electrolyte concentration, clay content, free iron-oxides and clay mineral species are all important factors involved in the hydraulic conductivity of soil. But the most important single factor for the contrasting soils was soil mineralogy. They found that the hydraulic conductivity changed very little with decreasing salt concentration and increasing SAR for the two tabular halloysite soils.

Bresler (1971) reported that swelling of soils containing clay and dispersion of the soil colloidal material alter the geometry of the soil pores and thus affect the intrinsic permeability of the soil. He deduced from the double layer theory that both swelling and particle dispersion increase as soil solution concentration and Ca$^{++}$/Na$^+$ ratio decrease. He further expressed that the hydraulic conductivity is affected not only by the intrinsic permeability, but also by the properties of the soil solution, such as fluid density and viscosity, which are also affected by the composition and concentration of solutes.

Shainberg and Klausner (1971) studied the relative effect of clay swelling and
dispersion on the permeability of soils. They suggested that the blockage of the pores, as a result of clay dispersion and movement, was the main mechanism which controlled the reduction in permeability when soils of low ESP values were leached with dilute salt solutions, while swelling was the dominant mechanism at high ESP values.

Velasco-Molina et al. (1971) studied the interacting effect of contrasting clay mineralogy, SAR, ESP, and electrolyte concentration on the dispersion of soil colloids. They found that montmorillonitic soils and micaceous soils disperse more in weak salt solution at low SAR values than do the kaolinitic-halloysitic soils high in iron-oxide. In the absence of electrolytes, soils dispersed in relation to their dominant clay minerals; montmorillonitic greater than halloysitic and kaolinitic greater than micaceous.

Casey (1972) reported that at any point, while in the liquid state, water may be carrying dissolved salts, and if water evaporated from the salt water mixture, the remaining salts will be more concentrated after evapotranspiration processes. It is the concentration increase that results in a soil salinity problem. He also pointed out that the water entering the soil may dissolve soil salts and carry them along through the soil down past the root zone. According to him, for any given salt concentration of applied water, there is some volume of that water, that is great enough to carry all the salts down through the root zone even after losses through evapotranspiration. This process was called as leaching, and it is fundamental to both soil salinity prevention and reclamation.
Emerson and Baker (1973) studied the favorable conditions for clay dispersion or migration when a loamy or sandy loamy soil, with low ESP values, was leached with dilute solutions. They reported two conditions that favor clay dispersion: (i) a sharp reduction in the concentration of the soil solution below the threshold concentration at which the clay particles flocculate; and (ii) a high concentration gradient between the dilute solutions of the macropores and the more concentrated solution in the micropores inside the aggregates.

Felhendler et al. (1974) found that clay dispersion in soils with low silt content was more pronounced than in soils with similar ESP and clay mineralogy, but with higher silt content. It suggests that dispersion is strongly dependent on soil texture and mineralogy.

Chen and Banin (1975) studied soil structure changes due to sodium calcium exchange in relation to hydraulic conductivity using scanning electron microscope (SEM). They found that reduction in hydraulic conductivity of soil leached with mixed NaCl-CaCl2 solutions of low electrolyte concentration are related fine particle dispersion and the formation of a more continuous network of these particles at higher SAR values. This causes blockage of larger pores in the soil and reduces the rate of water flow by increasing the proportion of small size pores. They reported that the changes in a sandy or clayey soil were quite similar. Dispersion of the fine particles seen to start at low SAR values, but the formation of the network becomes apparent only at SAR > 16.

Passioura (1976) studied the effects of dissolved salts on the hydraulic properties
of unripe marine soil. He used NaCl-CaCl₂ salts using 4 salt concentrations and cationic ratios, and he measured hydraulic conductivity after equilibration. He found that the saturated hydraulic conductivity decreased as either the total salts concentration of soil solution decreased or the cationic ratio increased. He also found that the ESP value of the soil was not only influenced by the cationic ratio but also by total salts concentration of soil solution. The ESP increased as either concentration decreased or cationic ratio increased. He found a second order curvilinear relation between the saturated hydraulic conductivity and the ESP. The decrease in hydraulic conductivity occurred in the ESP range from 12 to 60. He further investigated that in the reclamation of marine sodic soils, both leaching of salts and physical ripening are necessary requirements. In the early stage of ripening, the soil shows a poor permeability. This may be due to the unripe state in soil structure and the excessive amounts of sodium. It can be recognized that the soil hydraulic properties which determine either soil water flow or salts transport, have transient characteristics depending on both the physical ripening stage and the concentration and composition of salts in the soil solution.

Pupisky and Shainberg (1979) measured the changes in the hydraulic conductivity of a Red Brown sandy soil as a function of the concentration and SAR of the percolating solutions. The data showed that at high ESP's and at salt concentration above 0.01 N, swelling of the clay was the main mechanism responsible for hydraulic conductivity decrease. At low ESP and very dilute soil solution, dispersion and clay migration into the conducting pores were the main mechanisms responsible for
plugging the soil pores. Dispersion of the clay particles was possible only when the concentration of soil solution dropped below a threshold concentration at which the clay platelets flocculate. The dispersion of clay might lead also to an increase in hydraulic conductivity when a sandy soil is leached with distilled water.

Dass (1984), Dhir (1977), and Yadav (1980) investigated that irrigation with saline water decreases pH and increases the EC, SAR, and ESP of soil. The increase in EC of soil during the period of irrigation depends mainly on the salinity level of irrigation as well as the leaching fraction by irrigation with waters of high EC.

Frenkel et al. (1978), studying the effect of clay type and content, ESP, and electrolyte concentration on clay dispersion and soil hydraulic conductivity, concluded that the sensitivity of soils to excessive exchangeable sodium and low electrolyte concentration increases with clay content and bulk density. They also reported that although montmorillonitic soils are the most sensitive to sodic conditions, both neutral kaolinitic soils and vermiculitic soils are also sensitive to sodic conditions at low electrolyte concentration.

Frenkel et al. (1978) concluded that plugging of pores by dispersed clay particles is the major cause of reduced hydraulic conductivity in montmorillonitic, vermiculitic, and kaolinitic soils irrigated with sodic waters of questionable suitability (SAR’s of 10 to 30 and salt concentrations of 0 to 10 meq/litre). They found that the exact levels of exchangeable sodium and low electrolyte concentration increases with clay content and soil bulk density. The hydraulic conductivity of relatively coarse textured soils with ESP’s of 10 or more (clay percentages as low as 8) is also appreciably reduced by
dispersion at sufficiently dilute electrolyte concentrations.

Water-table and its management

Reeve and Bower (1960) found that there will be a decrease in SAR with dilution. They estimated that the SAR is inversely proportional to the square root of the dilution factor, and the equilibrium exchangeable sodium percentage (ESP) of a soil varies directly with some function of SAR, it follows that equilibration of a soil with successive dilutions of sea water or any high-salt water containing cations (Na\(^+\), Ca\(^{++}\), Mg\(^{++}\)) will result in corresponding reductions in ESP. They further reported that the amount of water required to attain a desired reclamation will depend, quite obviously, upon the concentrations of the several cations in the water and upon the exchange properties of the soil, including the initial exchangeable sodium status. They suggested that by beginning the leaching process with a water of sufficiently high electrolyte content, deterioration of the permeability rate can be prevented.

Meek et al. (1980) evaluated the effects of three water table depths of 30, 60, and 90-cm on growth of cotton. According to them optimal water-table depth was 90-cm. At water-table depths of 30 and 60-cm, seed cotton yield was reduced by 43 and 25 percent, respectively. The investigators also found that decreasing the water table depth to 90-cm increased the total uptake of N, P, K.

Kanwar et al. (1983, 1984) found that inadequate drainage systems were responsible for crop yield reductions at the tune of about one-third of the potential yields on heavy soils.
Campbell et al. (1985) studied nitrogen and phosphorus losses from a sandy, high water-table soil used for potato production under two water management systems. Inorganic nitrogen losses from the subsurface drainage - irrigation system were about 35 percent less than from the furrow irrigation system.

Bouwer and Asce (1987) stated that due to nonuniform irrigation applications and preferential flow, the deep percolating water reaches the ground water quickly and dissolved salts, nitrates, and pesticides become main groundwater chemical pollutants.

Jain and Dass (1988) reported that high salinity in soils and irrigation with saline water in arid and semi-arid regions have adverse effect on normal fruit production. As new areas come under irrigation, salinization problems increase, because of indiscriminate use of ground water and poor land and water management.

Fouss et al. (1988) listed the advantages of proper and timely control of subsurface drainage: (1) reductions in the frequency and the duration of excessive soil water in the root zone caused by rainfall, (2) prevention of the over drainage of the soil profile, (3) reduction of the need to pump subirrigation water, and (4) increases in rainfall-use efficiency.

Sharma and Swarup (1988) found that waterlogging decreased oxygen-diffusion rate; restricted root growth; and reduced ion uptake, especially of N, P, K, Ca\(^{++}\), Mg, and Zn; and led to greater absorption of Na\(^+\), Fe and Mn. The effect of waterlogging was also relatively pronounced at high alkalinity values.

Bhuiyan and Alagcan (1990) conducted experiments to investigate the response
of corn to shallow water-table encountered by farmers growing upland crops adjacent to irrigation canals or rice areas. They found that lowering the water depth slightly produced a strong negative response in both plant height and yield. The investigators indicated that during the vegetative growth state of corn, it was highly probable that corn yields higher than 7.3 t/ha could be achieved for an average water-table depth of 15-cm.

Ahmed et al. (1991) reported that in areas where canal supplies are deficient and the water table is high, a system to control the water table by subsurface drainage using the drainage effluent for irrigation, is an alternative possibility. Drainage and Reclamation Institute of Pakistan (DRIP) has designed and developed six farm-sized isolated drainage systems in lower Sindh, Pakistan where drainage effluent is reused for saline agriculture or is recirculated in the irrigation system.

Fate of fertilizers and pesticides in the soil-water environment

Harmsen and van Schrevan (1955) stated that the mineralization and immobilization of nitrogen is usually a microbial process and is influenced by soil physical, chemical, and biological conditions.

Laura (1974) observed that both the decomposition rate of organic matter and mineralization rate of nitrogen decreased due to increase in salinity.

MacKenzie and Viets (1974) reported that the composition and concentration of materials contained in surface drainage waters differ from those found in subsurface drainage waters. The slow movement of subsurface drainage water percolation
through the soil affords intimate and extended contact with clays, organic matter, and microorganisms. Soluble nutrients and other chemicals applied to or contained in the soil may be dissolved by soil water and leached from the soil profile. At the same time, some materials will be removed from solution by adsorption and the formation of precipitates. The composition of subsurface drainage water may also depend on the aeration status of the soil being drained. Water from a drain that flows continuously from a saturated soil profile may have a different composition than water from a drain that flows only intermittently and is exposed to aerated soil.

Baker and Johnson (1979) indicated that pesticide half-lives were about 2 weeks (except for atrazine, 1 to 2 months), with pesticides remaining concentrated in the top 5-cm.

Gilliam et al. (1979) studying the effect of drainage control on nitrate presence in agricultural fields of different soils with unique drainage properties, installed riser-type water-level control structures to raise the level of water to increase denitrification during winter. Nitrate-nitrogen loss through tile lines was greatly reduced from 25-40 to 1-7 Kg/ha in moderately well-drained soils because of reduction in effluent volume. In moderately well-drained soils, there was no indication of increased denitrification in the field. In poorly drained soils, drainage control had no effect on the soil profile oxidation-reduction processes but nitrate-nitrogen movement through drainage ditches decreased by approximately 50 percent.

Schwab et al. (1980) measured 1529 kg/ha sediment loss from plots with one meter deep drains, a reduction of 40% due to subsurface drainage. Annual losses of
nitrate-nitrogen, phosphorus, and potassium, respectively, occurred with one meter deep drains, were 18.7, 1.2, and 22.5 kg/ha. Subsurface drainage increased the loss of nitrate-nitrogen by 54 percent and reduced the loss of phosphorus and potassium by 45 and 29 percent, respectively.

Bottcher et al. (1981) measured average annual nitrogen and phosphorus losses of 8.66 and 0.22 kg/ha, respectively. Approximately 70 percent of the phosphorus loss was associated with sediments compared to 10 percent for nitrogen. The analysis showed that losses of sediments and nutrients were reduced by subsurface drainage. They recommended that on suitable soil types, subsurface drainage may well be a preferred best management practice for water quality control.

Schwab and Logan (1982) reported that sediment, phosphorus, and potassium losses from tile outflow were considerably less than from surface runoff, but nitrate losses were higher. Generally, subsurface drains reduced soil erosion and the loss of most plant nutrients on medium to heavy texture soil.

Bandyopadhyay and Bandyopadhyay (1983) reported that the mineralization and immobilization of nitrogen in soil is influenced by soil salinity. They found that the rate of both mineralization and immobilization of nitrogen in soil considerably reduced by soil salinity (ECe of 10 mmhos/cm) at 25°C and above. They observed that when fertilizer nitrogen was applied in soil a part of it was either lost or temporarily lost in soil under natural conditions even if no crop was grown.

Cohen et al. (1984) reported that agricultural pesticides are a significant cause of groundwater contamination due to leaching beyond the root zone into aquifers.
The EPA began to emphasize work on groundwater contamination by pesticides in 1979 after aldecarb and dibromochloropropane (DBCP) were found in the groundwater in various states.

Kanwar et al. (1985), studying the movements of nitrate-nitrogen in relation to tillage systems and fertilizer-application methods, found that in no-till plots had significantly more nitrate-nitrogen in the soil profile than did moldboard-plow plots after simulated 12.7-cm and 6.35-cm rainfalls.

So and Orchard (1985a;b) found rapid reduction in nitrate in pots with plants than in pots without plants under waterlogged conditions. They concluded that plants were able to take up nitrate even under waterlogged conditions.

Cohen et al. (1986) found that atrazine has been detected in five states at a residue range of 0.3-3.0 ug per liter. They reported that downward leaching was found to be largely responsible for atrazine residues at low levels detected in groundwater in many irrigated areas.

Donigian and Rao (1986) explained that the uptake, translocation, accumulation, and transformation of pesticides by plants affect the availability of pesticides for transport processes and plant processes can serve as both a sink and a source of pesticides residues available for transport.

Jury (1986) described the factors that influence the transport of chemicals in porous media. The physical and chemical properties that effect the fate of pesticides are solubility, vapor pressure, toxicity, adsorption rate, and soil reactivity. The second category would include environment conditions such as rainfall, soil properties,
temperature, and erosion rate. The final category can be called management influences, including the rate of pesticide application, method of application, cropping method, irrigation and/or drainage practices, and chemical used and its formulation.

Loudon et al. (1986) found that plant nutrients and soil amendments are leached from the soil by percolating water and conveyed to receiving streams. They also observed that rate of concentration was probably related to tillage methods.

Nofziger and Hornsby (1986) concluded that the depth to which chemicals move in soils depends in a complex way upon a number of soil, chemical, and weather factors. Soil properties that influence chemical movement include: pH, bulk density, field capacity and wilting point, volumetric water contents, and soil organic-carbon content. Properties of chemicals that influence their movement include: partition coefficient (Kd or Koc), and degradation half-lives. Climatic and cultural factors include plant root depth, daily rainfall and irrigation, and daily evapotranspiration amounts.

Ritter (1986) reported that atrazine and alachlor together accounted for 25 percent of all pesticides sold in the U.S. in 1982.

Williams et al. (1988) reported that there were at least 46 pesticides detected in groundwater in 26 states as a result of agricultural applications. Additionally, at least 32 pesticides have been found in 12 states as a result of misuse or point source from loading and rinsing activities.

Isensee et al. (1988) reported that groundwater contamination is predictable at sites where highly soluble pesticides are applied to very permeable soils. They showed
a major concern that low concentrations of less soluble but widely used pesticides were being detected in shallow aquifers under a wide range of agricultural and climatic conditions. According to them, three corn production herbicides, alachlor [2-chloro-2′6′-diethyl-N-(methoxymethyl)acetanilide], atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino)-S-triazine], and cyanazine [2-chloro-4 (cyano-1-methylamino)-6-ethylamino-S-triazine], fall into this category have been detected in groundwater in many states because of their wide application. They found that atrazine concentration in shallow groundwater was 0.2-1.8 ppb and that of alachlor was 0.0-0.3 ppb. These concentrations were far lower than the health advisory limits for atrazine (150 ppb) and alachlor (700 ppb).

Smith et al. (1988) reported that the soil properties influencing the pesticide transport are soil water content, bulk density of soil, permeability, clay content, organic matter content, and water retention. They found that atrazine concentration in the soil water at a depth of 61-cm reached 0.35 ppm after 19 days of application. They also reported that atrazine concentration of as high as 0.09 ppm was observed in the shallow groundwater nearly 16 months after application.

Bengtson and Southwick (1989) reported that atrazine losses were reduced by 55 percent by subsurface drainage. They concluded that subsurface drainage substantially reduced atrazine losses, and over two-thirds of the losses occurred within 30 days after herbicide application. They also found that the atrazine concentrations were substantially greater than the EPA advisories for drinking water.

Evans et al. (1989a) Summarized the results of ten studies representing
approximately 125 site-years of data collected on poorly drained soils in North Carolina. They found that fertilizer nutrient losses in conventional drainage outflow (free drainage) typically exceeded 20 kg N and 0.25 kg P per hectare per year. Controlled drainage was reported to have reduced these nutrient losses by 30 to 50 percent. In their another study, current estimates were that, controlled drainage was reducing agriculture’s contribution of nitrogen to North Carolina’s coastal waters by over one-half million kilograms annually (Evans, et al. 1989b).

Merva and Belcher (1990) observed the concentrations of nitrate, phosphorous, and potassium, in surface runoff, soil-water solution, and subsurface flow, as functions of subirrigated high water table and subirrigated low water table zones. Controlled drainage and high-water table conditions caused relatively low soil-water concentrations of nitrate, phosphorus, and potassium.

Kalita and Kanwar (1990) concluded from their studies that the influence of water table management practices on atrazine mobility was not clear although water table depth should affect the movement of atrazine into groundwater. The extent of atrazine leaching into groundwater varied with the water table position and management practices.

Ahmed and Kanwar (1991) investigated that nitrogen in fertilizers may be found in the form of free ammonia, urea, salts of ammonia, and nitrate. In warm aerated soils, urea hydrolyses to ammonium nitrogen and soil bacteria convert ammonium (NH₄) to nitrate in a few days or weeks, and volatilization losses can occur in the soil through biological reduction of nitrate to nitrous oxide (NO₂). Also excessive soil
water can cause the loss of nitrogen by denitrification.

Bengtson (1991) concluded from subsurface drainage experiments on silty alluvial soils in the Mississippi Valley, that subsurface drainage reduced surface runoff, soil and nutrient loss by substantial amount. He recommended that a complete subsurface drainage systems on certain soil types may be the preferred "best management practice" for improving the quality of water.

**Soil columns and effluent collection**

Hiler (1969) and Hiler et al. (1971) used a commercially available liquid level control system to hold the water at various heights in the soil column for studying crop-drainage requirements. To study nitrate transformations with a controlled water table, Meek et al. (1970) installed perforated plastic pipe in their columns at three heights. By closing or opening a drain they could control the water level at those heights. Barkle (1983) used a plexiglass cylinder, hydraulically connected to the columns, with stop-cocks at various levels, to control the water table at those levels. The stopcock at the desired water table level was opened and when the water level in the column rose above that desired, water flushed back through the system and drained through the open stopcock.

Huggenberger et al. (1972) applied the water at a constant rate with a pump to a fitted glass plate over the soil surface to evenly distribute the water. This allowed to approximate the boundary conditions of the model for which they were obtaining experimental data.
Logan and McLean (1973) sectioned the columns they had leached with labeled phosphate and saved the samples for analysis of phosphate content. Lopez-Avila, et al. (1986) performed a similar sectioning to test the soil for the pesticides applied in the leaching experiment. Emmerich (1980) sectioned columns leached with sewage sludge to determine the movement of heavy metals.

Misra et al. (1974a;b) used glass wool to distribute their influent and to eliminate soil erosion in their study on nitrate reduction.

Devenport et al. (1975) studied the effect of different media and temperature on denitrification under a constant flow rate. They collected effluent which was forced through horizontal columns under a piezometric head.

Wagenet and Starr (1977) used a glass disc with a constant-head burette to maintain a constant pressure at the influent end of the column as part of a system to control the water and gas regimes of a soil column.

Smith et al. (1985) used a peristaltic roller pump to apply water to the column through 20 hypodermic needles fixed above the soil surface. Though it was noted that this may set up preferential flow paths. For the soils studied the water appeared to disperse over the soil surface due to surface residues. For some studies more elaborate rainfall simulators are required. Similarly, Gaudet et al. (1977), Germann et al. (1984) used hyperdermic needles attached to a sheet metal cylinder that rotated for simulated rainfall. The number and size of the needles could be varied to produce different sprinkling rates. Andrieni and Steenhuis (1990) studied preferential flow under different tillage systems and did not want to bias the results by applying the "rainfall"
unevenly over the column surface. The simulator they used consisted of a catheter which traversed an entire column surface by oscillations through two perpendicular axes. Klocke et al. (1989) used a rotating drip irrigation system to apply water uniformly to their lysimeters. Liechtenstein et al. (1978) used a spray nozzle mounted above the soil surface to apply water. Several other studies (Boddy and Baker, 1990; Hubbard et al., 1989a; b; Shipitalo et al., 1990; Lesikar et al., 1991) have used rainfall simulators to apply water.

Smith et al. (1985), studying the effectiveness of disturbed versus undisturbed soils when used as filters for E. coli, fitted the bottoms of their columns with a collection funnel form which all of the effluent was collected and analyzed. Boddy and Baker (1990) and Hubbard et al. (1989) also used collection funnels in their upper root zone chemical transport studies.

Andreini and Steenhuis (1990) used a grid sampler fitted to the bottom of their columns, with effluent from each grid being directed to a separate sample bottle. In this way, they could look at differences in chemical concentrations not only as a function of time, but also as a function of cross-sectional location.

Shipitalo et al. (1990) used a similar procedure to determine the uniformity of water flow through their soil blocks and to study the differences in solute breakthrough with various rainfall scenarios in a structured soil with macropores.

Skaggs et al. (1978) reported a method for determining the drainable porosity on large undisturbed soil columns. Total porosity for a soil column is generally determined by methods that require a core sampler, unless the column is special-
ly, instrumented. Total porosity can be estimated using the bulk density and particle
density of the soil (Hillel, 1982; Klute, 1986). It can also be measured by the gas
pycnometer method (Klute, 1986). If a pore size distribution is required, the pressure
intrusion or water desorption methods can be used (Hillel, 1982; Klute, 1986).
PAPER 1: LARGE SOIL COLUMNS FOR HYDRAULIC
CONDUCTIVITY AND SOLUTE TRANSPORT STUDIES IN
THE LABORATORY
ABSTRACT

Numerous studies are being conducted that access the impact of agricultural chemicals (pesticides and fertilizers), on surface and groundwater contamination. Some studies have also been conducted investigating salt behavior in soil and irrigation water. Soil columns have been used to study chemical transport processes, develop strategies, and evaluate impacts related to agricultural chemicals fate and salt behavior in soils. With all prior and continuing work, researchers have not identified a uniform set of procedures for soil columns studies in the laboratory.

In this paper a method is described for constructing low-cost soil columns. A procedure was developed for packing columns uniformly to a desired bulk density. This procedure enables packing of different density layers in the same column. Uniformity and reproducibility of packing were determined by conducting tests of salt equilibrium, drainage porosity, and moisture content.
INTRODUCTION

The study of solute transport in laboratory soil columns needs dependable methods. A commonly used method for packing soil in a column is to tamp small increments of soil into the column. This method is tedious and usually results in layering of the soil. Moreover, reproducibility is virtually out of the question (Yaron et al., 1966). But careful packing can bring uniformity in column filling. A mechanical method, using a vibration technique for pot filling, was used by various investigators (Rosenberg, 1959 and 1960; Yaron and Maokadi, 1962). Jackson et al. (1962) improved on this method and used the combination of motorized tremic and vibrator block for good uniformity and column reproducibility. Their method did not, however, easily permit packing of layered soil columns.

Various soil column techniques (Cassel et al., 1974; Elrich and French, 1966; McMahon and Thomas, 1974; Smith et al., 1985) have compared results for both disturbed and undisturbed columns. Most of these techniques have a well developed set of procedures and have been described in detail in various studies (Belford, 1979; Berndt et al., 1976; Bouma and Dekker, 1981; Bowman, 1988; Brown et al., 1985; Buchter et al., 1984; Chinchester, 1977; Holmes et al., 1988; Lewis et al., 1990; Lowry and Finney, 1962; Manor et al., 1990; Marek et al., 1988; Murphey et al., 1981; Palmer and Magette, 1989; Robertson et al., 1974; Russel, 1991; Schneider et al., 1988; Swallow et al., 1987; Tackett and Fryrear, 1965; Walker et al., 1990; Zwick et al., 1984). Different modifications of some of these techniques have been
made with the need of the study.

Soil columns have been used for many purposes including the estimation of hydraulic and other physical parameters (Ward et al., 1983; Germann and Beven, 1981; Bouma et al., 1977; Bouma and Wosten, 1979; Zobeck et al., 1985; Perrous and Zegelin, 1984; Wells and Skaggs, 1976; Skaggs et al., 1978; Bouma and Dekker, 1981) and even to study the effects of acid rain on soil microbial activity (Bitton and Boylan, 1985).

Many researchers simply collect leachate by gravity drainage. Smith et al. (1985), Boddy and Baker (1990), and Hubbard et al. (1989) fitted the bottoms of their columns with a collection funnel from which all of the effluent was collected and analyzed. Davenport et al. (1975) collected effluent which was forced through horizontal columns under a piezometric head.

For some purposes it is necessary to apply a matric pressure to the soil column system. Mansell et al. (1968) fitted the bottom of their columns with a porous plate to provide a constant outflow pressure to a system for controlling the aeration and unsaturated water movement in soil columns. Brown et al. (1985) installed ceramic cups in the bottom of their monoliths as part of the leachate collection system. In several studies porous cups or plates have been used in the drainage system with a surrounding media such as diatomaceous earth to spread the pressure evenly over the entire soil surface (Cassel et al., 1974; Hiler, 1969; Hiler et al., 1971; Ritchie et al., 1972). Many other studies have used porous plates of one type or another for similar reasons (Emmerich, 1980; Gaudet et al., 1977; Germann and Beven, 1981; Klocke et
In some studies, soil suction lysimeters or porous ceramic cups have been used to collect soil solution from within the column. Smith et al. (1989), Meek et al. (1970), and Alhajjar et al. (1990) used one bar porous ceramic cups to collect effluent from several different depths within the soil column, in order to determine the pollution potential of atrazine and nitrates at different soil depths with slight modifications. Andreini and Steenhuis (1990) used a grid sampler fitted to the bottom of their columns, with effluent from each grid being directed to a separate sample bottle. As a result, they could look at differences in chemical concentrations as a function of time, and cross-sectional location. Shipitalo et al. (1990) used a similar procedure to determine the uniformity of water flow through soil blocks and to study the differences in solute breakthrough with various rainfall scenarios in a structured soil with macropores.

Water application methods for column studies also vary. Huggenberger et al. (1972) applied the water at a constant rate with a pump to a glass plate over the soil surface to evenly distribute the water. Misra et al. (1974a;b) used glass wool to distribute influent and to eliminate soil erosion. Wagenet and Starr (1977) used a frittered glass disc with a constant-head burette to maintain a constant pressure at the influent as part of a system to control the water and gas regimes of a soil column. Aburime and Steenhuis (1985) used a mariotte device to apply water at a constant head in an air-tight system to study the flow of water and chemicals in heterogenous soil. Mansell et al. (1968) and Wagenet and Starr (1977) used a similar device as part
of a system to control aeration and unsaturated water movement in the column. Bouma and Wosten (1979) used a mariotte device to maintain continuous, shallow ponding on the cores that they used for the study of breakthrough curves on clays with different macrostructure. Wells and Skaggs (1976) used a Mariotte siphon to apply water through the bottom of a soil core at a constant head.

Several investigators employed a rainfall simulator of some type. Smith et al. (1985) and Gaudet et al. (1977) used a peristaltic roller pump to apply water to the column through 20 hypodermic needles fixed above the soil surface. To minimize the effect of preferential flow paths, Germann et al. (1984) used hyperdermic needles which were attached to a sheet metal cylinder that rotated.

Elaborate rainfall simulators have also been reported. Andrieni and Steenhuis (1990), studying preferential flow under different tillage systems, used a simulator consisting of a catheter which traversed an entire column surface by oscillations through two perpendicular axes. Klocke et al. (1989) used a rotating drip irrigation system to apply water uniformly to their lysimeters. Liechtenstein et al. (1978) used a spray nozzle mounted above the soil surface to apply water. Several other studies have used rainfall simulators to apply water (Boddy and Baker, 1990; Hubbard et al., 1989a; b; Shipitalo et al., 1990; Lesikar et al., 1991).

In studies, which required that the water table be held above the bottom of the column, Hiler (1969) and Hiler et al. (1971) used a commercially available liquid level control system to hold the water at various heights in the soil column. To study nitrate transformations with a controlled water table, Meek et al. (1970) installed perforated
plastic pipe in their columns. Barkle (1983) used a plexiglass cylinder, hydraulically connected to the columns, with stopcocks at various levels, to control the water table.

Columns can be instrumented to allow for measurement of soil moisture, wet bulk density, soil matric potential, and many other characteristics in a variety of ways. Weighing lysimeters have been designed and built for several studies (Harrold and Dreibelbis, 1958; Harrold and Dreibelbis, 1967; Owens, 1960; Armijo et al., 1972; Melancon et al., 1986; Marek et al., 1988). Neutron probes have been used for soil moisture determinations (Hiler, 1969; Hiler et al., 1971; Ward et al., 1983; Wells et al., 1986). The gamma probe has also been used for both soil moisture content and bulk density (Gaudet et al., 1977; Germann et al., 1984; Misra et al., 1974a;b; Ward et al., 1983; Wells et al., 1986). Smith et al. (1989) used a Time Domain Reflectometry probe to measure soil moisture contents.

Soil moisture tension is generally measured using tensiometers at different depths in a column (Hiler, 1969; Hiler et al., 1971; Meek et al., 1970; Aburime and Steenhuis, 1985; Belford, 1979; Wells and Skaggs, 1976; Ward et al., 1983). Bouma et al. (1983) used tensiometers to characterize the infiltration and redistribution patterns of water.

Soil temperature has been measured by a variety of methods including thermistors (Belford, 1979; Cannell et al., 1980; Lowry and Finney, 1962), thermocouple (Klocke et al., 1989; Hiler, 1969; Hiler et al., 1971), and thermometers (Meek et al., 1970). Mansell et al. (1968) and Wagenet and Starr (1977) used column instrumentation for the simultaneous control of the soil water and air regimes.
Kanwar et al. (1989a) designed and installed soil air access chambers for soil air sampling to determine transient-state oxygen diffusion. Other studies have also used air samplers (Belford, 1979; Meek et al., 1970; Lowry and Finney, 1962; Wagenet and Starr, 1977).

Some researchers also used alternatives for air sampling. Hiler (1969) used a platinum microelectrode technique to determine oxygen diffusion rates within the soil column without collecting a sample. Mansell et al. (1968) used an oxygen analyzer in the gas outflow of their columns. Other specialized instrumentation is possible for specific objectives. Wilson et al. (1981), in their study of the fate and transport of volatile organic, designed a system that would minimize the loss of the compounds. They used teflon gas-sampling bags immersed in water at both ends of a sealed column.

Column sectioning is often done for chemical studies. In most cases this involves the use of some sort of dye tracer applied and leached through the column. After the dye has passed through the column, the column is cut into thin sections (Andrelini and Steenhuis, 1990; Bouma et al., 1977; Jardine et al., 1988). Germann et al. (1984) stripped all of the bromide applied from each soil layer and created bromide profiles. Boddy and Baker (1990) sectioned the column and took pictures of each surface for macropores. Logan and McLean (1973) sectioned the columns for the analysis of phosphate content. Lopez-Avila et al. (1986) performed a similar sectioning to test the soil for the pesticides applied in the leaching experiment. Emmerich (1980) sectioned columns leached with sewage sludge to determine the movement of heavy
metals. Lesikar et al. (1991) set up enough disturbed columns for analysis after every chemical application. Column sectioning is, however, costly.

Porosity can be determined by a variety of methods. Skaggs et al. (1978) report a method for determining the drainable porosity on large undisturbed soil columns. Total porosity can be estimated using the bulk density and particle density of the soil (Hillel, 1982; Klute, 1986). It can also be measured by the gas pycnometer method (Klute, 1986). If a pore-size distribution is required, the pressure-intrusion or water desorption methods can be used (Hillel, 1982; Klute, 1986).

This paper describes a simple and inexpensive method that enables reproducible packing of soil columns either uniformly or in layers of different bulk density and texture. Uniformity of packing can be checked by flow rate of water through different columns of like treatments. Salt equilibration and the soil porosity pattern were used to authenticate the uniformity of column packing. This chapter gives details of a column preparation method and tests of column reproducibility.
MATERIALS AND METHODS

Column preparation

Soil columns were prepared for two sets of experiments: (1) columns for a series of hydraulic conductivity and solute transport experiments, and (2) columns for water-table management experiments for salinity control and nitrate fate studies.

These soil columns were prepared by using PVC (PIP-80) pipes of 20-cm diameter (Figure 1a). To conduct hydraulic conductivity experiments, pipes were cut in the lengths of 115-cm each. For water-table management experiments, pipe lengths of 75 and 45-cm were used (Figure 1c).

To make these columns leak proof and inexpensive, the materials used were PVC pipe, PVC primer and PVC cement.

The column bottoms, which are very important to this research project, were difficult to build. Round pipes pieces of about 25-cm length were saved and were cut to open vertically to form one wall (Figure 1b). These pieces of PVC pipes were then heated in the oven at 350°C for about 7 minutes and were straightened on smooth fine board using a pressing iron. After these pipe pieces were flattened into rectangular sheets, they were marked into circles of little more than 20-cm in diameter and were cut using electric saw (Figure 1d). The edges of these circular plates were carefully smoothed, using a grinder to bring them into a size that fits exactly inside 20-cm diameter PVC pipe to be used for soil columns (Figure 1e).

Another set of 7.5-cm long PVC pipe pieces were used for molding into rings.
These rings were prepared in such a way that they tight fit to the columns fastening the pipe walls. On both ends of a ring, circular PVC plates described above were glued. The upper plate was perforated by drilling numerous holes of about 5.0 mm diameter each (Figure 1f). The lower bottom plate was drilled in the center for leachate collection in the bottom of the column (Figure 1g). A semi-hard tube was inserted in the bottom hole and tightly glued to prevent leaking.

Before the perforated plate was glued to the ring and after inserting the semi-solid tube in the bottom, paraffin was liquified and poured in the dishes formed by the ring and bottom plate assembly. After the wax solidified, a funnel-like structure was made by manually shaping the paraffin. A built-in funnel was prepared and empty container for leachate dripping from upper perforated plate was then introduced into the assembly (Figure 1j).

After the funnel arrangement was made and checked for thorough emptying, the upper perforated plate was glued in place. A layer of fiber glass window screen was then cut in a circular shape (which was 25-cm in diameter) so that it could cover the perforated plate and overlap down around the ring. A layer of cheese cloth the same size as the screen described above was put on top of the fiber glass screen. Covering the perforated hard PVC plate covered with screen and cheese cloth assured a fine passage of solutes and also checked the entry of soil particles with solutes. Thus, column bottoms were prepared and glued with PVC cement after priming with PVC primer. The bottom was slid in the bottom end of the column by pressing down uniformly. This arrangement ensured a leakproof bottom and a built-in funnel of fine
quality. On top of the perforated plate-screen-cloth arrangement, a 5-cm depth of column was filled with coarse sand to prevent from sealing of perforations by colloidal particles (Figure 2).

In the case of columns used for water-table management studies manufacturing the bottom was a less complicated process. Only one PVC plate on the lower end of the ring was glued. Because the leachate was collected from a drain installed horizontally at the top of the porous plate, no funnel arrangement was required. However, influent was injected through semi-solid tubes inserted from the wall of the column in the lower end of the column (Figure 3).

Various piezometers were installed horizontally at the desired depths of the columns by an elbow-tube arrangement glued in place (Figure 4).

**Soil and column packing**

The soil used in the hydraulic conductivity and solute transport experiment was sandy loam. It was collected from the bank of Squaw Creek near Ames, Iowa. A one meter square of land was dug to the depth of about 1.07 meters in depth increments of 15-cm. The soil dug for each increment was put in separate plastic bags covered with cloth bags. The collected soil was then brought to the laboratory for further processing.

The soil from each depth increment was spread on a table for drying. When the soil moisture reached about 10% by weight, the soil was thoroughly crushed and passed through a 3.175 mm sieve and stored in separate metal containers lids.
The soil used for the water-table management experiment was brought from two sites; one from Iowa State University farm near Ankeny, and the second soil was from Squaw Creek as described earlier. The Ankeny soil was collected from Subsurface Drainage Project area (Ahmad and Kanwar, 1991). Since the depths of soil required in water-table management experiment were 30-cm and 60-cm, a pit of one meter square was dug to a depth of 60-cm. The soil was collected as a function of depth.

The soil was packed in the columns to the required bulk density in layers by tamping the dried soil in the known volume. The successful method of packing soil in the columns was by tamping small amounts of soil at a time. For these large columns of 100-cm length one must work slowly. Each time about the same amount of soil is to be put in the column and spread on top of the previous soil. The column bottom was pounded on the smooth floor, using the same number of impacts from same of height on each occasion. Measurements of the empty height in the column were taken after every packing of about 1-cm.

Salt equilibrium

To create simulated conditions with that of salinity levels closely comparable to those in the field, it is necessary to maintain salt equilibrium at desired salinity levels. There is no fully satisfactory method in the literature as to how to bring an equilibrium of salt concentration. In most of the studies, soil has been equilibrated before solute transport tests were conducted. Bischoff et al. (1984) equilibrated soil columns with 50 pore volumes of leachate, but they did not mention the tests of
columns with 50 pore volumes of leachate, but they did not mention the tests of equilibrium whether or not equilibrium was really achieved.

Various methods of salt equilibrium were tested. For example, in a 30 cm long column with uniform soil packing, salt solution of known concentration was applied by ponding the solution on the top of the column. Five pore volumes were leached, but salt equilibrium could not be achieved. In another test for salt equilibrium, a salt solution was applied on top of 30-cm column in very small pulses for 24 hours (five pore volumes). Again, however, equilibrium could not be achieved. The changes in concentrations were observed with respect to variation in depth as well as at the same depth. The reason for not obtaining equilibrium was that the soils without salts, when leached with salt solutions, take considerably longer time for ripening. The ripened soils easily come into equilibrium. For this purpose, long soil columns of 100-cm length were filled with soil of uniform moisture content of 12 percent by weight. Salt was added to the soil at desired concentrations of 3200 and 6400 ppm and was mixed thoroughly. These columns were used to make hydraulic conductivity measurements for one month. This soil was ripened thoroughly. Subsequent equilibria were easy to obtain through leaching salt solutions from bottom upward and top downward by passing equivalent to 3 pore volumes of solution. If these columns are left for settling, the salts move downward and lower horizons contain higher concentrations than the upper ones when evaporation was not allowed. Under evaporative conditions, salt equilibria get disturbed in two ways, concentration increase in bottom layers and top layers while intermediate layers decrease.
In solute transport experiments the soil extracts were tested by sampling from different depths using piezometers installed at 15-cm depth intervals. In initial tests the salt concentrations were determined by sectioning the columns in 2-cm depth intervals after drainable water was removed out of the columns. Column sectioning is very tedious, time consuming and costly. The columns were destroyed each time which is not an economical thing.

For testing the columns for their performance, the salt equilibrium tests were conducted on salt-ripened soil columns as described earlier. Two salt concentrations of 19,200, and 38,400 ppm NaCl and CaCl₂ (1:1 ratio by weight) were used in 2 treatments using three columns in each treatment. These soil columns were first saturated with respective salt concentrations from bottom of the columns with 1-cm increments every hour by raising water table using reservoirs with control valve. When water level in the columns reached the top, the soil solution samples were taken at different depths of the columns from preinstalled piezometers. The samples were then analyzed for chloride concentrations. These same salt solutions were then leached through the columns under each treatment for 36 hours. Once again, soil solution samples were taken and analyzed for chlorides.

The drainable porosity tests were conducted three times by collecting water from saturated columns of three salt treatments, using 0, 3200, and 6400 ppm first time and then using 0, 19,200, and 38,400 ppm salt concentrations in percolating water, and again 0, 19,200, and 38,400 ppm salt concentrations in soil flushed with fresh water. The hours of saturations of columns were 18, 36, and 42. Each time
drained water from saturated columns was collected and measured for drainable porosity.

Soil moisture content test was conducted on layered soil columns of different bulk densities. The soil columns with three salt concentrations of 0, 3200, and 6400 ppm were leached with fresh water for one month by ponding water on top of the columns at constant depth of 5-cm. When drainable water drained out of the columns, the six soil layers in the depth increment of 15-cm and 10-cm bottom layer was taken out of the columns, mixed separately for each treatment and was analyzed for moisture content.
RESULTS AND DISCUSSION

The column preparation study reported here describes the steps by which the columns were prepared and tested for their accuracy. It was an effort toward preparing low-cost and easily handled soil columns.

From the review of literature it was found that the reproducibility of columns is very important without which the laboratory studies are unreliable. Also leachate collection methods are improved over earlier studies. Thus, major emphasis was given to the preparation of leak-proof columns, soil filling/packing in the columns, and replicating of treatments rather than working on a single experiment unit to minimize errors. The step by step procedures for column preparation are shown diagrammatically (Figures 1 through 4).

It is difficult to obtain soil uniformity in the column characteristics. With careful handling of soil and packing procedures, however, one can minimize the variation of column behavior. The column testing criteria established here were drainable porosity, uniformity in obtaining salt equilibria, and evenness of water flow and moisture content.

Salt equilibrium in the columns

Figures 5a and 5b show the patterns of obtaining salt equilibria for salt concentrations of 19,200 and 38,400 ppm, respectively. It was observed that by saturating the soil columns from the bottom the salt concentrations decreased as the
distance from column bottom increased. By applying same concentrations of salts from the top on already salt saturated columns, the salt equilibria were obtained within an acceptable limits. The salt concentrations increased with increases in depth below the top of the columns. This type of trend is expected because salts settle down under gravity. The analysis of variance of chloride concentrations is given in Tables 1 and 2 for bottom and top saturation methods, respectively.

Table 1 shows that there was nonsignificant difference in replications. This suggests that the replications within a treatment were alike and yielded similar chloride concentrations. Table 1 also shows that the treatments were highly

Table 1. Analysis of variance on chloride concentrations at different soil profile depths for salt equilibrium when uniformly packed sandy loam soil columns were saturated with different salt solution concentrations from bottom.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>10081145</td>
<td>5040573</td>
<td>2.58 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>5320953087</td>
<td>2660476544</td>
<td>1360.70 ****</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>16622984</td>
<td>4155746</td>
<td>-</td>
</tr>
<tr>
<td>DEPTH</td>
<td>5</td>
<td>3154475</td>
<td>630895</td>
<td>0.32 N.S.</td>
</tr>
<tr>
<td>TRT*DEPTH</td>
<td>10</td>
<td>3760259</td>
<td>376026</td>
<td>0.19 N.S.</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>30</td>
<td>58656988</td>
<td>1955233</td>
<td>-</td>
</tr>
</tbody>
</table>
significant.

This is an expected result because salt concentrations were different under each treatment. This shows that chloride concentrations under 3200 ppm, and 6400 ppm concentrations were significantly different from each other. The depth was nonsignificant. Moreover, the interaction between treatment and depth was nonsignificant. The analysis of variance on chloride concentrations for top saturation of soil columns is given in Table 2.

Table 2 indicates that there was nonsignificant difference in replications. It also indicates that the replications within a treatment were alike and yielded similar

Table 2. Analysis of variance on chloride concentrations at different soil profile depths for salt equilibrium when uniformly packed sandy loam soil columns were saturated with different salt solution concentrations from top.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>225270</td>
<td>112635</td>
<td>1.31 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>5827673894</td>
<td>2913836947</td>
<td>8143.80 ****</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>343006</td>
<td>85751</td>
<td>1.08 N.S.</td>
</tr>
<tr>
<td>DEPTH</td>
<td>5</td>
<td>870009</td>
<td>201389</td>
<td>1.78 N.S.</td>
</tr>
<tr>
<td>TRT*DEPTH</td>
<td>10</td>
<td>3233292</td>
<td>609416</td>
<td>5.38 **</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>30</td>
<td>2297277</td>
<td>76576</td>
<td>-</td>
</tr>
</tbody>
</table>
chloride concentrations. Table 2 also shows that the treatments were very highly significant, it is an expected result because salt concentrations were different under each treatment. This indicates that chloride concentrations under 3200 ppm, and 6400 ppm concentrations were significantly different from each other. The depth was nonsignificant. The interaction between treatment and depth, however, was significant.

**Drainable porosity**

Figure 6 shows changes in drainable porosity with respect to the time and method of soil saturation in the columns and salt concentrations in the soil or percolating water. The drainable porosity (cm³) after 18 hours of saturation from bottom of the columns in depth increments of 3-cm and from top for another 18 hours resulted in about 2000 cm³ of water discharged from the pores. After saturating the soil columns slowly at depth increments of 1-cm/hour from bottom with salt solutions of 0, 19,200, and 38,400 ppm and then saturating from top for another 36 hours resulted in increase of drainable porosity in all treatments respective to salt concentrations. It signifies that the drainable porosity increased with more saturation period and salt concentrations. After another leaching process of 42 hours from top with fresh water, the drainable porosity reduced to about 1700 cm³ because of the reason that much of the salts leached out of the columns, dispersion action also reduced and the soil was settled down which reduced the porosity by increase in bulk density from 1.35 g/cm³ to 1.40 g/cm³. The analysis of variance of drainable porosity
Table 3. Analysis of variance on drainable porosity of uniformly packed sandy loam soil columns saturated with different salt solution concentrations as a function of cumulative time of leaching.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>772033</td>
<td>386016</td>
<td>3.95 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>164325</td>
<td>82162</td>
<td>0.84 N.S.</td>
</tr>
<tr>
<td>ERROR</td>
<td>4</td>
<td>90979</td>
<td>22745</td>
<td>-</td>
</tr>
</tbody>
</table>

is given in Table 3.

Table 3 indicates that there was nonsignificant difference in replications. This suggests that the replications within a treatment were alike and yielded similar amounts of water from soil pores from all columns. Table 3 also shows that the treatments were also nonsignificant showing no difference in drainable porosity values. This indicates that all columns acted in the same way and that when the soil columns were packed uniformly, the differences were only of salt concentrations that were the variable factors in different tests.

Soil moisture content

The soil moisture content test was applied for three treatments of 0, 3200, and 6400 ppm salt concentrations (NaCl and CaCl₂, 1:1 ratio by weight). This test was
conducted to examine moisture distribution in the columns after ponding water on top of the columns at uniform depth of 5-cm for 30 days. The initial moisture content in the soil was 12 percent. The analysis of variance of moisture content at different column depths is given in Table 4.

Table 4. Analysis of variance on soil moisture content with respect to different salt concentrations in layered soil columns and profile depths.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REP</td>
<td>2</td>
<td>47.52</td>
<td>23.76</td>
<td>13.57  ****</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>18.82</td>
<td>9.41</td>
<td>5.38   ***</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>76.89</td>
<td>19.22</td>
<td>-</td>
</tr>
<tr>
<td>DEPTH</td>
<td>6</td>
<td>429.77</td>
<td>71.63</td>
<td>10.31  ****</td>
</tr>
<tr>
<td>TRT*DEPTH</td>
<td>12</td>
<td>21.32</td>
<td>1.78</td>
<td>1.23   N.S.</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>36</td>
<td>63.03</td>
<td>1.75</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4 indicates that there was significant difference in replications. This suggests that the replications within a treatment were not alike and yielded different volumetric moisture content percent. Table 4 also shows that the treatments also showed significant difference. The depth showed very highly significant difference. However, the interaction between treatment and depth was nonsignificant. The
moisture content should be constant under saturated conditions of the soil in different columns at all depths if the soils were of uniform texture, particle size distribution, and bulk density. However, under this test the soil parameters of bulk density were not the same and salt concentrations in the soil were different that influenced the moisture content in different treatments.
CONCLUSIONS

Low-cost columns were constructed successfully using PVC pipes. The empty columns were tested and found to be leak-proof and suitable for use.

The columns were packed with sandy loam soil at desired bulk densities for a series of experiments. These columns were subjected to tests on salt equilibrium, drainage porosity, and moisture distribution.

Soil uniformity and column reproducibility tests for salt equilibrium indicated that salt distribution at all depths was almost uniform at different salt concentrations. However, to achieve salt equilibrium at any given salt concentration, the salts need to be applied with water flowing from the bottom of the column first and then with water coming from the top under gravity flow under a constant head. The drainable porosity test indicated that replications and treatments had no significant difference. This test indicated uniformity of soil packing and had uniform drainable porosity with respect to individual treatment. The moisture content test also indicated that there was no significant difference in replications and treatments showing that the soil packing was uniform in the columns.
REFERENCES


Jackson, R.D., Reginato, R., and Reeves, W.E. 1962. Mechanized device for
packing soil columns. USDA Bull. No. 41-42. United States Department of Agriculture, Washington, D.C.


Russell, M.H. 1991. The Du Pont intact soil coring machine (DISCM). Description summary and personal communication. Du Pont Agricultural Products Experiment Station, Wilmington, DE.


method for evaluating agroecosystem effects of an industrial waste plant. 
Plant and Soil 77: 395-399.
Figure 1. Step-wise preparation of soil column, a. PVC pipe, b. PVC pipe for straightening, c. straightened pipe, d. three bottom plates, e. precisely cut and ground plate, f. upper plate, g. lower plate, h. PVC pipe piece for a ring, i. ring, j. ring with built-in funnel.
Figure 2. A soil column.
Figure 3. A soil column with piezometers.
Figure 4. Water table depths (a) 60-cm depth, (b) 30-cm depth.
Figure 5a. Salt equilibria in soil columns with 19,200 ppm salts, applying salt solutions from bottom and then from top.
Figure 5b. Salt equilibria in soil columns with 38,400 ppm salts, applying salt solutions from bottom and then from top.
a. Cumulative Saturation Time (Hours)

b. Drainable Porosity (% of soil volume)

Figure 6a,b. Drainable porosity (percent pore volume) as influenced by cumulative time of saturation and salt concentration treatments.
PAPER 2: MOVEMENT OF SALTS THROUGH A LAYERED SOIL
ABSTRACT

A laboratory study was conducted to understand the mechanics of salt transport in large disturbed soil columns. Nine PVC columns measuring 20-cm in diameter and 115-cm long were filled with sandy loam soil sieved through 3.175 mm mesh to form seven layers of different bulk densities (1.47, 1.50, 1.52, 1.52, 1.53, 1.53, and 1.52 g/cm$^3$). The top six soil layers have the depth increments of 15-cm each and the bottom layer was 10-cm in depth.

Three salt concentrations of 0, 3,200, and 6,400 ppm were maintained in the soil by mixing NaCl and CaCl$_2$ salts (1:1 ratio by weight). A constant ponding of fresh water was maintained on top of columns. The leachate was collected from the bottom of the columns every 24 hours for a period of 31 days.

The results of this study show that after 31 days of constant leaching the salts flushed to the lower layers of the columns indicating a reclamation process of salt affected soils.
INTRODUCTION

Infiltration and hydraulic conductivity (K) of soils are important soil properties needed to predict the flow of water or solutes through the soil profile. The variability and heterogeneity of most field soils affect leaching rates, regardless of the method used for their measurements. The leaching of salts from a soil not only is a function of the soil texture, but also is dependent on soil structure, salinity levels of soil, and salt composition of soil solution.

It is well documented that the concentration and the composition of the percolating soil solution through the soil profile have a great influence on the stability and the conductance of the soil (Pupisky and Shainberg, 1979). McNeal and Coleman (1966) found that increasing the Sodium Adsorption Ratio (SAR) and decreasing the electrolyte concentration of the percolating solution induced a decrease in soil permeability. McNeal et al. (1966) found strong positive correlation between soil swelling, expandable clay content, and the K values. Various investigators (Gardner, 1945; Gardner et al., 1959; McNeal et al., 1966; Shainberg et al., 1981) suggested that the reduction in permeability was due to clogging of conducting pores. They found that when soils of low ESP values were leached with dilute salt solution, swelling was the dominant mechanism. Emerson and Baker (1973) found favorable conditions for clay dispersion or migration when a loam or sandy loam soil, with low ESP values, was leached with dilute solutions. They reported that clay dispersion is favored by sharp
reduction in the concentration at which the clay particles flocculate and a high concentration gradient between the dilute solutions of the macropores and the more concentrated solution in the micropores inside the aggregates. Felhendler et al. (1974) were of the view that clay dispersion in soils with low silt content was more pronounced than in soils with similar ESP and clay mineralogy, but with higher silt content. Velasco-Molina et al. (1971) found that montmorillonitic soils and micaceous soils disperse more in weak salt solutions at low SAR values than do the kaolinitic-halloysitic soils high in iron oxides. In the absence of electrolytes soils dispersed in relation to their dominant clay minerals: montmorillonitic > halloysitic-kaolinitic > micaceous.

Likewise, Frenkel et al. (1978) concluded that the sensitivity of soils to excessive exchangeable sodium and low electrolyte concentration increases with clay content and bulk density. They also concluded that although montmorillonitic soils are the most sensitive to sodic conditions, both neutral kaolinitic soils and vermiculitic soils are also sensitive to sodic conditions at low electrolyte concentrations. Soils with exchangeable sodium equal to around 15 percent or more of their exchangeable capacity and low in soluble salts have been shown to exhibit poor physical properties (U.S. Salinity Laboratory Staff, 1954). This effect is attributed to hydrolysis of the exchangeable sodium, causing the soil colloids to disperse. Sodium affected soils which contain appreciable quantities of soluble salts tend to remain flocculated unless the salts are leached from the soil. It indicates that the dispersing effect of sodium is conditioned by other salts in solution and the presence of dispersible material in the
soil. Thus, both swelling and dispersion phenomena are related and either can reduce the leaching rate under circumstances.

Previous laboratory studies have been conducted on very thin pads of soil or small soil columns. From a thorough review of literature, it is clear that soil column studies, containing the entire profile depth (between the soil surface and subsurface drain to a depth of 100 to 120-cm), have not been conducted for layered soils. Therefore, simulated profile conditions were created for one-dimensional vertical flow through long soil columns for investigating the transport of salts under saline conditions. The main objective of this study was to investigate the effects of salts on water movement through a layered soil packed in a long soil column and on processes responsible for reclamation of soils. The results of this study were also used to understand the phenomenon of salt movement through the layered soil under a constant depth of ponding.
MATERIALS AND METHODS

Column assembly

The experiments were conducted in the laboratory using large soil columns of 100-cm length, filled with soil in six soil layers of 15-cm each, plus a seventh layer of 10-cm in thickness. These six soil layers represented soil bulk densities of 1.47, 1.50, 1.52, 1.52, 1.53, 1.53, and 1.52 g/cm³, respectively beginning from the top of soil surface.

The soil used for the experiment was collected from the bank of Squaw Creek in the NW corner of the city of Ames, Iowa. The textural class of the soil was sandy loam to loam. The in-situ bulk density of the soil was measured by taking soil samples with a 75 mm diameter core sampler. The soil from one meter square area was dug in depth intervals of 15-cm and was brought to the laboratory in plastic bags. Each soil segment was spread on the floor separately for air drying. After air drying, the soil was crushed and passed through 3.175 mm mesh sieve and was stored in plastic cans with lids for further use in column experiments. Then NaCl and CaCl₂ salts (1:1 ratio by weight) were added to this soil (which was already weighed for each depth increment of the column) to bring the required concentrations of salts. The soil used for this experiment had some natural salt content (although it does not classify a saline soil). The initial total dissolved solids measured for each depth increment of the soil column were at concentrations of 811, 495, 696, 664, 647, 854, and 1458 ppm in
seven depths starting from soil surface, respectively.

The columns used in this study were made from PVC pipes of 20-cm diameter. Which were cut in lengths of 115-cm for building the columns. The column bottoms were prepared from the leftovers of these pipes. Two circular plates were used for constructing the column bottom, one of which was used to drill holes to make it perforated, and other piece was used to pass a leachate tube at the bottom of the column. A 5-cm thick ring was placed in between these plates to be firmly glued to the column pipe. Figure 1 gives the details of the column assembly.

Taking one column as an experiment unit, in all 9 soil columns were prepared by filling with the salt containing soil at additional salt concentration of 0, 3200, and 6400 ppm at the required bulk density for each layer. Thus, each concentration represented three columns as three replications. Efforts were made to make sure that a crust did not form at any point during the column filling process. The important thing to consider was that the soil should not be dried below a moisture content of 7% by weight in layered soil packing. If this threshold is not satisfied, soil grains become very loose, and in the process of stirring and tamping, fine particles move together. Impermeable crusts are created which, in turn, affect water flow (Hanks and Bowers, 1962). After filling the soil columns with salt containing soil, the columns were covered with plastic sheets to minimize evaporation.
Salt leaching experiment

The experiment was conducted to investigate the leaching of salts through each soil column by using a constant depth of water ponding. A constant head was maintained by using a control valve system which maintained a constant water level of 5.0 cm at the surface of soil at all times.

The leachate was collected at the bottom of the column through a built-in funnel and tubing arrangement (Figure 1). The effluent was collected every 24 hours and data on effluent volumes (for each time increment) were collected for leachate calculation. This experiment was conducted over a period of 31 days. The effluents were analyzed for electrical conductivity (EC), calcium (Ca^{++}), sodium (Na^{+}), and pH. Cation ratios (Na^{+}/Ca^{++}) were calculated from Na^{+} and Ca^{++} concentrations data. Data on leachate volume were collected as a function of the time.
Percolation rates through the column were measured as a function of the soil electrolyte concentrations and time. Some pertinent properties of the soil that was packed in the columns are given in Table 1.

From the data given in Table 1, the texture classifications are sandy loam for layers 1, 2, and 5, and loam for layers 3, 4, 6, and 7, respectively, layer 1 being the surface layer. The combined effect of Sodium Adsorption Ratio (SAR) and salt

Table 1. Depth-wise particle size distribution (percent) of soil profile.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>0.50 mm</th>
<th>0.25 mm</th>
<th>0.106 mm</th>
<th>Coarse Silt</th>
<th>Fine Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15</td>
<td>4.70</td>
<td>44.50</td>
<td>18.80</td>
<td>17.92</td>
<td>7.44</td>
<td>6.64</td>
</tr>
<tr>
<td>15-30</td>
<td>2.43</td>
<td>31.20</td>
<td>20.50</td>
<td>25.63</td>
<td>9.84</td>
<td>10.40</td>
</tr>
<tr>
<td>30-45</td>
<td>0.80</td>
<td>21.30</td>
<td>20.00</td>
<td>28.70</td>
<td>15.04</td>
<td>14.16</td>
</tr>
<tr>
<td>45-60</td>
<td>0.80</td>
<td>21.20</td>
<td>20.50</td>
<td>29.70</td>
<td>13.80</td>
<td>14.00</td>
</tr>
<tr>
<td>60-75</td>
<td>0.90</td>
<td>27.80</td>
<td>23.40</td>
<td>23.58</td>
<td>13.04</td>
<td>11.28</td>
</tr>
<tr>
<td>75-90</td>
<td>1.20</td>
<td>25.30</td>
<td>19.90</td>
<td>32.08</td>
<td>9.00</td>
<td>12.52</td>
</tr>
<tr>
<td>90-100</td>
<td>1.40</td>
<td>27.80</td>
<td>21.60</td>
<td>30.87</td>
<td>8.49</td>
<td>9.84</td>
</tr>
</tbody>
</table>
concentrations on percolation rates changes were measured and interpreted in the light of leachate analyses of electrical conductivity (EC) at 25°C, pH, cations (Na⁺ and Ca²⁺), and cationic ratio (Na⁺/Ca²⁺). The soil solution cationic composition in SAR term is commonly used to describe the cationic composition effect on soil hydraulic conductivity (U.S. Salinity Laboratory Staff, 1954).

**Electrical conductivity**

The EC is the function of total dissolved solids and a measure of soil salinity. The EC is usually recorded at 25°C as a reference unit of measurement. Figure 2 indicates the trends of EC with respect to time for leachate samples collected from all points averages of three column measurements. It indicates that under control treatment, T1, (where no additional salts were added to the soil, the EC of the leachate was almost constant with time, as time progressed the natural salts initially present in the soil profile were leached out and EC showed a slight reduction with time. For treatment No. 2, where salts were added to bring the concentrations of column soil to 3200 ppm (EC = 5 mmhos/cm). The EC values in the leachate increased with time. Since the amount of solvent (water) infiltrated slowly through the column, the leaching of salts to lower layers of the column with the water may have resulted in high solute density and viscosity of the leachates (Bresler, 1971). This may have also resulted in lowering the K values. Furthermore, for columns with an initial concentration of 6400 ppm the infiltrating water carried salts to the lower layers which resulted in the
reduced movement of water through the column. This gave an increased EC, Na\(^+\), Ca\(^{++}\) amounts in the leachate that may have reduced the K values of lower layers. The analysis of variance on electrical conductivity of leachate with respect to time is given in Table 2.

Table 2. Analysis of variance on electrical conductivity of leachate from layered sandy loam soil profiles with different salt concentrations leached with fresh water.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>17633</td>
<td>8817</td>
<td>2.05 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>57357</td>
<td>28678</td>
<td>6.68 *</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>17172</td>
<td>4293</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>13</td>
<td>17233</td>
<td>1326</td>
<td>34.98 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>26</td>
<td>11260</td>
<td>433</td>
<td>11.43 ****</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>204</td>
<td>7752</td>
<td>38</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2 indicates that there was nonsignificant difference in replications. This suggests that the replications within a treatment were alike, yielding similar leachate amounts. Table 2 also indicates that the treatments were highly significant. This shows that EC values under control, 3200 ppm, and 6400 ppm concentrations were significantly different from each other. The time had highly significant difference
indicating that the EC values differed significantly with respect to time. The regression models for three treatments ($T_1$, $R^2 = 0.97$; $T_2$, $R^2 = 1.00$; and $T_3$, $R^2 = 0.97$) are given as follows:

\[
\begin{align*}
\text{EC (Control)} &= 1.161 - 0.05575 (T) + 0.002175 (T^2) \\
\text{S.E} &= \pm 0.018558 \quad \pm 0.005303 \quad \pm 0.000343 \\
\text{EC (3200 ppm)} &= 2.20683 + 4.37593 (T) - 0.1454 (T^2) \\
\text{S.E} &= \pm 0.610852 \quad \pm 0.17456 \quad \pm 0.011319 \\
\text{EC (6400 ppm)} &= 4.71664 + 5.13583 (T) - 0.0725 (T^2) \\
\text{S.E} &= \pm 3.196746 \quad \pm 0.91352 \quad \pm 0.059239
\end{align*}
\]

**Sodium ion concentration in leachate**

Sodium ($\text{Na}^+$) is a monovalent cation and plays a major role in saline and sodic soils. Sodium causes dispersion of soil particles, deterioration of soil structure, and reduction of hydraulic conductivity of soil due to its dispersing effect.

Figure 3 indicates that the $\text{Na}^+$ ion leaches through soil profile at an increasing rate with time. When compared with 6400 ppm salt concentration columns, the $\text{Na}^+$ concentration in the leachate from the 3200 ppm columns shows a gradual increase. On the other hand, the $\text{Na}^+$ concentration in the leachate from the control columns was almost constant. The analysis of variance on $\text{Na}^+$ concentration in the leachate is given in Table 3.

Table 3 shows that replication and treatment effects were nonsignificant,
Table 3. Analysis of variance of Na⁺ ion concentration (ppm) in leachate from layered soil profiles with different salt concentrations leached with fresh water as a function of time.

<table>
<thead>
<tr>
<th>S.V</th>
<th>D.F</th>
<th>S.S</th>
<th>M.S</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>198102148</td>
<td>99051074</td>
<td>1.24 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>505575491</td>
<td>252787745</td>
<td>3.15 N.S.</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>320797295</td>
<td>80199324</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>13</td>
<td>72184458</td>
<td>5552651</td>
<td>21.86 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>26</td>
<td>53756696</td>
<td>2067565</td>
<td>8.14 ****</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>204</td>
<td>51813237</td>
<td>253987</td>
<td>-</td>
</tr>
</tbody>
</table>

thereby indicating that treatments had nonsignificant effect on the Na⁺ concentration in the leachate.

The regression models for three treatments (T₁, R² = 0.89; T₂, R² = 0.67; T₃, R² = 0.99) are given as follows:

Na⁺ (control) = 68.1545 - 1.3056 (T) + 0.046544 (T²)

S.E = ± 1.008826

Na⁺ (3200 ppm) = 931.555 + 205.9355 (T) - 5.023 (T²)

S.E = ± 152.3305

Na⁺ (6400 ppm) = 1527.84 + 254.8899 (T) + 0.9801 (T²)
Calcium ion concentration in leachate

Calcium (Ca++) is a divalent cation. Iowa soils are calcareous in nature and calcium is a predominant ion in the soil. Calcium does not pose any hazardous effect on crop growth under normal circumstances. Calcium with different anions, however, acts differently. Calcium in chemical compounds of carbonates and bicarbonates increases soil pH as well as changes saline soils into alkaline categories. Calcium stabilizes soil, maintains aggregate structure, controls dispersion caused by Na⁺, and increases hydraulic conductivity of soil resulting in the increased leaching of salts in the leachate.

Figure 4 shows that calcium concentrations in the leachate increased with time, the highest concentration being in 6400 ppm salt concentration soil columns. With more and more Ca++ accumulation at exchange sites with time and dispersion of soil particles with sodium additions, sodium is released to the percolating water depending on the rate of water movement through the soil columns. The calcium concentrations in the leachate was linearly proportional to the salt concentrations in the soil. The analysis of variance of Ca behavior in the soil columns treated differently is given in Table 4.

Again, Table 4 shows that salt concentrations had no effect on replications and treatments. It suggests that replications and treatments were alike in their behavior.
However, the effect of time was highly significant. The best-fit regression models for three treatments of salt concentrations (T_1, R^2 = 0.98; T_2, R^2 = 0.93; T_3, R^2 = 0.99) are given as follows:

- Ca^{++} (Control) = 216.5839 - 22.227 (T) + 0.96498 (T^2)
  S.E = ± 5.59333 ± 1.59838 ± 0.18365

- Ca^{++} (3200 ppm) = 1252.214 + 249.406 (T) - 2.4883 (T^2)
  S.E = ± 259.3851 ± 74.1234 ± 4.80673

- Ca^{++} (6400 ppm) = 920.9505 + 395.253 (T) + 2.0927 (T^2)
  S.E = ± 178.8075 ± 51.0971 ± 3.31352

Table 4. Analysis of variance of Ca^{++} ion concentration (ppm) in leachate from layered sandy loam soil profiles with different salt concentrations leached with fresh water as a function of time.

<table>
<thead>
<tr>
<th>S.V</th>
<th>D.F</th>
<th>S.S</th>
<th>M.S</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>438668072</td>
<td>219334036</td>
<td>1.08 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>685295106</td>
<td>342647553</td>
<td>1.69 N.S.</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>810983077</td>
<td>202745769</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>13</td>
<td>181820265</td>
<td>13986174</td>
<td>16.62 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>26</td>
<td>134894026</td>
<td>5188232</td>
<td>6.17 ****</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>204</td>
<td>171675046</td>
<td>841544</td>
<td>-</td>
</tr>
</tbody>
</table>
Sodium/Calcium ratio in leachate

Sodium and calcium are the major players in the leaching process of salts and hydraulic conductivity. As the Na\(^+\)/Ca\(^{2+}\) ratio decreases, calcium content increases, thereby stabilizing the soil particles maintaining aggregates structure. In high sodium soils, however, the particles are dispersed which with increasing calcium proportions that settle down in the soil pores. In case the particles lodge in the pores, the movement of solutes is hindered. If particles do not fill the pores, the hydraulic conductivity is maintained constant.

Figure 5 indicates that in control treatment, the Na\(^+\)/Ca\(^{2+}\) ratio increased with time but became constant after about 10 days due to the fact that the percolating water contained more calcium than sodium. At salt concentrations of 3200 and 6400 ppm, the Na\(^+\)/Ca\(^{2+}\) ratio in the leachate decreased with time. The analysis of variance of Na\(^+\)/Ca\(^{2+}\) ratio as a function of time is given in Table 5.

Table 5 shows that the replication and treatment effects were nonsignificant. It is also the case that treatment and time interactions were nonsignificant. Only time effect was significant. The regression models for three treatments (T\(_1\), R\(^2\) = 0.95; T\(_2\), R\(^2\) = 0.94; and T\(_3\), R\(^2\) = 0.93) are given as follows:

\[
\text{Na}^+/\text{Ca}^{2+} \quad \text{(Control)} = 0.2545 + 0.0693 (T) + 0.0019 (T^2)
\]
\[
\text{S.E} = \pm 0.02927 \quad \pm 0.00836 \quad \pm 0.00054
\]

\[
\text{Na}^+/\text{Ca}^{2+} \quad \text{(3200 ppm)} = 1.8978 - 0.115 (T) + 0.0019 (T^2)
\]
\[
\text{S.E} = \pm 0.10324 \quad \pm 0.0295 \quad \pm 0.00191
\]
Table 5. Analysis of variance on Na\(^+/\)Ca\(^{++}\) ratio in the leachate from layered soil profiles with different salt concentrations as a function of time.

<table>
<thead>
<tr>
<th>S.V</th>
<th>D.F</th>
<th>S.S</th>
<th>M.S</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
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<td>8.31</td>
<td>4.15</td>
<td>0.2770  N.S.</td>
</tr>
<tr>
<td>TRT</td>
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<td>7.55</td>
<td>0.1440  N.S.</td>
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<tr>
<td>ERR(a)</td>
<td>4</td>
<td>9.23</td>
<td>2.31</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>13</td>
<td>10.99</td>
<td>0.85</td>
<td>2.73***</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>26</td>
<td>11.75</td>
<td>0.45</td>
<td>1.46 N.S.</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>78</td>
<td>24.12</td>
<td>0.31</td>
<td>-</td>
</tr>
</tbody>
</table>

\[
\text{Na/Ca}^{++} (6400 \text{ ppm}) = 2.3035 - 0.219 (T) + 0.00837 (T^2)
\]
\[\text{S.E} = \pm 0.07677 \quad \pm 0.02194 \pm 0.00142\]

**pH of leachate**

One of the outstanding physiological characteristics of the soil solutions is its reaction. The importance of soil reaction have long been recognized (Brady, 1974). Three conditions are possible: acidity, neutrality, and alkalinity. The presence of salts, especially calcium, magnesium, and sodium carbonates, also gives a preponderance of hydroxyl ions over hydrogen ions in the soil solution. Thus, pH changes with respect
to salt concentrations and time are important to study.

Figure 6 indicates that the pH values in the leachate decreased with time under all treatments. The chlorides of Na⁺ and Ca²⁺ bring about acidic reaction in the soil. As the concentration of the salts in the leachate (NaCl and CaCl₂) increased, the pH decreased. The analysis of variance of pH trends for leachate with respect to replicated treatments is given in Table 6.

Table 6 on the analysis of variance on pH shows that column salt concentrations had significant effect on the pH of the leachate. The regression models for three treatments ($T_1$, $R^2 = 0.87$; $T_2$, $R^2 = 0.92$; and $T_3$, $R^2 = 0.87$) are given as follows:

Table 6. Analysis of variance on pH of leachate from layered soil profiles with different salt concentrations as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F</th>
</tr>
</thead>
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<td>1.69</td>
<td>0.67 N.S.</td>
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<tr>
<td>TRT</td>
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<td>143.91</td>
<td>71.96</td>
<td>28.69 **</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>10.03</td>
<td>2.51</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>13</td>
<td>9.88</td>
<td>0.76</td>
<td>18.72 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>26</td>
<td>1.92</td>
<td>0.07</td>
<td>1.82 *</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>204</td>
<td>8.28</td>
<td>0.04</td>
<td>-</td>
</tr>
</tbody>
</table>
pH (Control) = 8.0776 - 0.0297 (T)
S.E = ± 0.0516 ± 0.01474

pH (3200 ppm) = 6.9598 - 0.0867 (T) + 0.0024 (T^2)
S.E = ± 0.0712 ± 0.02034 ± 0.00132

pH (6400 ppm) = 6.4591 - 0.0229 (T) - 0.0027 (T^2)
S.E = ± 0.5551 ± 0.15861 ± 0.01029

Reclamation of salts from soil profiles

The purpose of this study was to understand the process of leaching salts for soil reclamation. Figure 8 indicates that salts leached down in the lower layers in both salt concentrated treatments of 3200 and 6400 ppm. By maintaining 5-cm ponding depth of fresh water on the surface of soil at 70°F temperature, a soil with 6400 ppm dissolved solids can be reclaimed to 35-cm depth to grow shallow rooted crops like wheat, barley, and oats. In the case of 3200 ppm salt concentration the corresponding reclaimed depth would be 60-cm where almost all field crops could be successfully grown provided drains are installed to catch percolating water. Under these salt conditions corn, cotton, rice, soybeans, sugarcane, and wheat can grow at potential yield levels (Maas, 1986). For 50 percent yield, however, all these crops could be grown up to a rooting depth of 70-cm under 6400 ppm salt treatment. The major hazard of salts to crops is encountered when the top 10-cm soil contains more than 2000 ppm salt concentration. This is especially critical at the stage of seed emergence.
At later stages of plant growth, if the intervals of irrigation are reduced, plants do well. This is the case even if salinity levels exceed 10,000 ppm. From the results of this study one can recommend that the water be ponded on saline soils at the depth of 5-cm during winter months when evaporation losses are minimum to reclaim soils of about 6400 ppm. The water requirement for leaching salts and evaporation would be about 15-cm (5.6 inches) for 3200 ppm salt concentration in the soil and about 18-cm (7.0 inches) for 6400 ppm salt concentration soil of sandy loam texture with bulk density of 1.50 to 1.53 g/cm³.
CONCLUSIONS

The electrical conductivity of leachate and the trend of sodium and calcium ions increased with time. However, cation ratio (Na⁺/Ca++) decreased as the salt concentration increased in the leachate. Also leachate pH decreased with an increase in salt concentration.

It was concluded that with constant ponding at 5-cm of fresh water for 31 days the salts can be leached to lower layers in the soil profile and soil reclaimed to the depth of about 60-cm in 6,400 ppm salt treatment columns and 100-cm in 3,200 ppm salt treatment. This process would help successful growth of the majority of field crops.
REFERENCES


U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. U.S. Salinity Laboratory Handbook 60. United States Department of Agriculture, Washington, D.C.

Figure 1. A soil column.
Figure 2. Electrical conductivity (EC, mmhos/cm) of leachate with respect to salt concentrations and time in layered sandy loam soil columns leached with fresh water.
Figure 3. Sodium ion concentration in leachate with respect to salt concentrations and time in layered sandy loam soil columns leached with fresh water.
Figure 4. Calcium ion concentration in leachate with respect to salt concentrations and time in layered sandy loam soil columns leached with fresh water.
Figure 5. Cation (Na/Ca) ratios for leachates with respect to salt concentrations and time in layered sandy loam soil columns leached with fresh water.
Figure 6. pH of leachates with respect to salt concentrations and time in layered sandy loam soil columns leached with fresh water.
Average salt concentration at different profile depths in layered sandy loam soil columns after constant leaching for 31 days with fresh water.
PAPER 3: EFFECTS OF SOIL SALT CONCENTRATIONS ON SATURATED HYDRAULIC CONDUCTIVITY OF UNIFORMLY PACKED SANDY LOAM SOIL
A laboratory study was conducted to understand the mechanics of salt transport in large disturbed soil columns. Nine PVC columns measuring 20-cm in diameter and 115-cm long were filled with thoroughly mixed sandy loam soil sieved through 3.175 mm mesh sieve at a bulk density of 1.35 g/cm$^3$. Three salt concentrations of 0, 3,200, and 6,400 ppm were maintained in the soil by mixing NaCl and CaCl$_2$ salts (1:1 ratio by weight). Saturated hydraulic conductivity was measured under a constant head of 5-cm of fresh water. The leachate was collected from the bottom of the columns every hour for a period of 18 hours.

The results of this study showed that salt concentration influenced the saturated hydraulic conductivity of the soil. The electrical conductivity of the leachate increased with time and with leaching of salts to lower layers in the soil columns.
INTRODUCTION

The hydraulic conductivity (K) of a soil is an important soil property and has been studied extensively. It is well known that the concentration and composition of the percolating solution or soil solution have a great influence on the stability and K of a soil. Water soluble salts move with water in porous media. Different salts act differently, however, when they come in contact with soil particles, or soils behave differently when they come in contact with different cations particularly Na\(^+\), Ca\(^{++}\), and Mg\(^{++}\).

Soils with a high concentration of dissolved solids may have reasonable water transmission rates below the soil surface due to release of electrolytes from the soil (Gardner, 1945; Martin and Richards, 1959; Reeve, 1960). On the other hand, these same soils may have very low infiltration rates at the soil surface because of high particle dispersion and sealing caused by rainfall or irrigation water of very low salt concentrations. McNeal and Coleman (1966) found that increasing the sodium adsorption ratio (SAR) and decreasing the electrolyte concentration of the percolating solution induced a decrease in soil K values. Such changes were more pronounced in soil containing expandable 2:1 layer silicates, especially montmorillonite clays, than in soils containing kaolinite or sesquioxides. A strong positive correlation was found by McNeal et al. (1966) between soil swelling, expandable clay content, and the K sensitivity, reflecting the importance of the montmorillonite group as responsible for
the reduction in $K$. The reduction in $K$, however, occurred also at low ESP values, where no appreciable swelling is expected. McNeal et al. (1966) and Shainberg et al. (1971) suggested that the reduction in $K$ was due to clogging of the conducting pores either by in-situ mineral swelling or by migration of clay platelets which accumulated and decreased the pore sizes.

Dispersion is strongly dependent on soil texture and mineralogy. Felhendler et al. (1974) found that clay dispersion in soils with low silt content was more pronounced than in soils with similar ESP and clay mineralogy, but with higher silt content. The interacting effect of contrasting clay mineralogy, SAR, ESP, and electrolyte concentration on the dispersion of soil colloids was studied by Velasco-Molina et al. (1971). They found that montmorillonitic soils and micaceous soils disperse more in weak salt solutions at low SAR values than do the kaolinitic-halloysitic soils high in iron oxide. In the absence of electrolytes soils dispersed in relation to their dominant clay minerals: montmorillonitic $>$ halloysitic-kaolinitic $>$ micaceous. Similarly, Frenkel et al. (1978), studying the effect of clay type and content, ESP, and electrolyte concentration on clay dispersion and soil hydraulic conductivity, concluded that the sensitivity of soils to excessive exchangeable sodium and low electrolyte concentration increases with clay content and bulk density. They concluded also that although montmorillonitic soils are the most sensitive to sodic conditions, both neutral kaolinitic soils and vermiculitic soils are also sensitive to sodic conditions at low electrolyte concentration. Moreover, Frenkel et al. (1978) showed that clay dispersion and movement in distilled water were most pronounced in the nonacid kaolinitic soils.
Emerson and Baker (1973) studied the favorable conditions for clay dispersion or migration when a loam or sandy loam soil, with low ESP values, was leached with dilute solutions. They found that a sharp reduction in the concentration at which the clay particles flocculate and a high concentration gradient between the dilute solutions of the macropores and the more concentrated solution in the micropores inside the aggregates influenced water movement in the soil.

It is generally recognized that the high levels of exchangeable sodium lead to soil structural deterioration, which is accompanied by a reduction in the water movement through the soil profile (Naghshineh-Pour et al., 1970). There is a lack of quantitative information relating soil characteristics to water transmission properties under saline conditions.

It is a common knowledge that K of a saturated soil as measured in the laboratory may vary continuously with time (Allison, 1947; Bodman, 1937; Christiensen, 1944; Fireman and Bodman, 1939; Fireman, 1944; Quirk and Schofield, 1955). Among the factors responsible for the K variation have been cited the progressive deterioration of soil aggregation in which cation interaction between soil and the flowing solution may play a part, the effects of the soil microorganisms and changes in volume of the entrapped air.

Several other researchers have also demonstrated that K values measured within a single soil series varies by several orders of magnitude (Baker, 1978; Nassenhzadeh-Tabrizi and Skaggs, 1983; Sisson and Wierenga, 1981; Warrick et al., 1977; Young, 1976). Taherian et al. (1976) have reported that field measurements of K are subject
to soil variations that may be larger than the differences between the methods. Thus, laboratory methods seem to be better suited for investigating flow characteristics.

Several methods have been developed over the past 4 years to measure in-situ K values using the single and/or double auger-hole methods, piezometer method, and multiple well technique (Bouwer and Jackson, 1974; Kirkham et al., 1974). Also, several methods are available to measure K in the absence of a water table, such as air-entry permeameter, double-tube method, ring infiltrometer, and well-permeameter methods (Bouwer and Jackson, 1974). Some of these methods have been improved for rapid measurements of K (Carter et al., 1983; Topp and Sattlecker, 1983). Most of these methods have been used with various degrees of success (Backlund et al., 1986; Reynolds and Elrick, 1985). Some of the limitations of these methods include larger water requirement and the need for at least two operators to run the tests (Bouwer and Jackson, 1974). Through the recent development of new techniques (Merva, 1979; Talsma and Hallam, 1980; Reynolds and Elrick, 1985) have removed most of these limitations. Elrick et al. (1984), and Reynolds and Elrick (1985) have developed the Guelph permeameter for in-situ measurement of K. This method measures the steady-state rate of water flow of a shallow, cylindrical well in which a constant depth of water is maintained. In shallow depths soil porosity, structure, organic matter status and permanence of strata buildup are altogether different from the soil below the immediate plowed layer.

The K can be determined by several methods. The falling head and constant head infiltration methods (Klute, 1986) are standardized procedures. Bouma and
Dekker (1981) described a method for measuring the vertical and horizontal saturated hydraulic conductivity of undisturbed soil cores. Zobeck et al. (1985) compared several methods for determining hydraulic conductivity, two of which used large soil columns or blocks.

Both swelling and dispersion phenomena are related and either can reduce the $K$ under proper circumstances. Laboratory studies for examining these phenomena have been reported in the past, but most studies have been conducted on very thin pads of soil or small soil columns. From a thorough review of the literature, it is clear that soil column studies containing the entire profile depth (between the soil surface and subsurface drain to a depth of 100 to 120-cm) have not been conducted. Therefore, simulated profile conditions were created for one-dimensional vertical flow in long soil columns for determining flow patterns needed for predicting salt transport and $K$ under saline conditions. The main objective of this research work was to study the effects of soil salt concentrations on $K$ values of a sandy loam soil packed in long soil columns.
A saturated hydraulic conductivity experiment was conducted in the laboratory on soil columns of 115-cm length. These soil columns were filled with disturbed sandy loam soil in a uniform bulk density of 1.35 g/cm$^3$.

The soil columns were built using PVC pipe of 20-cm diameter in the lengths of 115-cm (soil profile 100-cm). The bottoms of these soil columns were made from the same PVC pipe leftovers. Two circular plates and a ring were used for constructing a column bottom. One plate was used to drill holes to make it perforated and the other plate was used to pass a leachate tube in the center of the bottom plate. A built-in funnel was prepared in the bottom for collecting leachate. The bottom plate was glued to a 5-cm thick ring and the container so prepared was filled with melted paraffin. When the paraffin solidified, it was scraped to make a funnel and then another plate was glued to complete the bottom assembly. This bottom was installed in the column and the top of the bottom was covered with a fibre glass screen and cheese cloth. Above the screen arrangement a 3-cm thick coarse sand layer was provided to prevent sealing of screen. Figure 1 shows the column assembly.

The soil used for the experiment was collected from the bank of Squaw Creek in the NW corner of the city of Ames, Iowa. The textural class of the soil was sandy loam. The soil from one meter square area was dug to a depth of one meter and was brought to the laboratory in plastic bags and it was spread on the floor for air drying.
After air drying, the soil was crushed and passed through 3.175 mm mesh sieve and was stored in plastic cans with lids. The soil used for this experiment had some natural salt content (although it will not classify a saline soil). The initial total dissolved solids were at a concentration of 736 ppm. The particle size distribution of the soil is given in Table 1. Before the soil was packed in the columns, NaCl and CaCl₂ (1:1 ratio by weight) in the concentrations of 3200 and 6400 ppm was maintained in the soil by thorough mixing for two salt level treatments. Third treatment (control) columns without salts were also packed. The soil moisture content was maintained at 9 percent by weight (gravimetric). The three treatments of 0, 3200, and 6400 ppm salt concentrations were obtained in the soil before packing the soil in the columns. Three replications were used for each treatment and saturated hydraulic conductivity measurements were made after saturating the columns with fresh water for 18 hours by raising water table from the bottom of the columns in increments of 3-cm every 30 minutes. When the water reached the top of the columns, the columns were left for 48 hours for saturation.

Hydraulic conductivity measurements were made for 18 hours using constant head of 5-cm of fresh water on top of the columns. The head was maintained by using a reservoir with control valve. The leachate from each column was collected from the bottom every hour and measured for its volume. The K values were calculated, using standard method based on Darcy's law. All water samples were analyzed for electrical conductivity (EC), Ca⁺⁺, Na⁺, and pH values. The Na⁺/Ca⁺⁺ ratios were calculated from Na⁺ and Ca⁺⁺ data.
Laboratory K values of sandy loam soil were measured as a function of soil electrolyte concentrations and time. The textural class of the soil was sandy loam. The combined effect of Sodium Adsorption Ratio (SAR) and salt concentrations on K changes were measured and interpreted in the light of leachate analyses of electrical conductivity (EC) at 25°C, pH, cations (Na⁺ and Ca⁺⁺), and cationic ratio (Na⁺/Ca⁺⁺). The soil solution cationic composition in SAR term is commonly used to describe the cationic composition effect on soil hydraulic conductivity (U.S. Salinity Laboratory Staff, 1954). The SAR values of soil solution for 3200 and 6400 ppm (NaCl and CaC₂ salts) were 2.55 and 3.60, respectively.

**Electrical conductivity**

The EC is a function of total dissolved solids and a measure of soil salinity and is usually recorded at 25°C as a reference unit of measurement. Figure 2 indicates the trends of EC with respect to time for leachate samples collected from three treatments. Due to the fact that the natural salts in the soil dissolved in water more as the time progressed, in control treatment, the EC values increased with time. Treatment No. 2, where salts were added to bring the concentrations of column soil to 3200 ppm (EC = 5 mmhos/cm), the EC values increased with time bringing the maximum EC value of about 2 mmohs/cm by the end of 14 hours. Since the amount of solvent (water)
infiltrated at a decreased rate through the columns as compared to treatment No. 1, resulted in more salts leaching to lower horizons and adding to percolating water and increasing EC values with time. Similarly, in columns with an initial concentration of 6400 ppm (EC = 10 mmhos/cm) increased EC values were observed in the leachate with time as in treatment No. 2, but in treatment No. 3 positive linear trend was observed. Analysis of variance on electrical conductivity of leachate with respect to time is given in Table 1.

Table 1 shows that there was nonsignificant difference in replications of individual treatments. It suggests that the replications within a treatment were alike

Table 1. Analysis of variance on electrical conductivity of leachate from uniformly packed sandy loam soil columns with different salt concentrations leached with fresh water as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
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<td>9.90</td>
<td>4.95</td>
<td>0.11 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>8025.55</td>
<td>4012.78</td>
<td>89.97 ***</td>
</tr>
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<td>ERR(a)</td>
<td>4</td>
<td>178.41</td>
<td>44.60</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>13</td>
<td>2301.42</td>
<td>177.03</td>
<td>108.65 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
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<td>1763.98</td>
<td>67.85</td>
<td>41.64 ****</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>204</td>
<td>332.39</td>
<td>1.63</td>
<td>-</td>
</tr>
</tbody>
</table>
and yielded similar EC values with time. The treatments of 0, 3200, and 6400 ppm were significantly different. The time was highly significant. The EC from one time to the other significantly differed. Also the interaction between time and treatment was very highly significant. The regression models for three treatments ($T_1, R^2 = 0.98; T_2, R^2 = 0.99; \text{ and } T_3, R^2 = 1.00$) are given as follows:

$$EC (\text{Control}) = 0.85748 - 0.0093 (T) + 0.0057 (T^2)$$
$$S.E = \pm 0.0548 \pm 0.0156 \pm 0.00101$$

$$EC (3,200 \text{ ppm}) = 2.02263 - 0.2908 (T) + 0.05575 (T^2)$$
$$S.E = \pm 0.25877 \pm 0.07394 \pm 0.00479$$

$$EC (6,400 \text{ ppm}) = 1.6194 + 1.8167 (T) - 0.0132 (T^2)$$
$$S.E = \pm 0.4616 \pm 0.13192 \pm 0.00855$$

**Sodium ion concentration in leachate**

Sodium ($Na^+$) is a monovalent cation, which plays a major role in saline and sodic soils. Sodium causes dispersion of soil particles, deteriorates soil structure, and reduces hydraulic conductivity of soil due to its dispersing effect.

Figure 3 indicates that the Na^+ ion leached through soil profile at an increasing rate with time. The Na^+ concentration in the leachate from the 3200 ppm and 6400 ppm show similar trends of positive linearity but higher values for 6400 ppm. But in control, the Na^+ in the leachate from the columns was almost constant. The analysis of variance on Na^+ concentration in the leachate from movement through the three
soil treatments is given in Table 2.

Table 2 shows that replications were nonsignificant and treatments showed significant difference, indicating that the replications were alike and behaved in the same way in each treatment. Treatments were not alike in showing a significant difference. Time and interaction of time with treatments were very highly significant showing that Na⁺ movement with respect to time was different for each treatment as well as the interaction of time and treatment was also significantly different for each treatment and each time interval. The regression models for three treatments (T₁, R²
= 0.66; T_2, R^2 = 0.99; T_3, R^2 = 1.00) are given as follows:

Na\(^+\) (control) = 124.533 - 12.087 (T) + 0.9002 (T^2)
S.E = ± 11.4814 ± 3.28098 ± 0.21276

Na\(^+\) (3,200 ppm) = 518.852 - 45.402 (T) + 12.254 (T^2)
S.E = ± 61.9644 ± 17.70729 ± 1.14828

Na\(^+\) (6,400 ppm) = 441.253 + 429.91 (T) + 30.018 (T^2)
S.E = ± 130.6131 ± 37.32477 ± 2.42042

**Calcium ion concentration in leachate**

Calcium (Ca\(^{++}\)) is a divalent cation. Iowa soils are calcareous in nature and calcium is a predominant ion in the soil. Calcium does not pose any hazardous effect on crop growth. But the calcium with different anions act differently. Calcium in chemical compounds of carbonates and bicarbonates increases soil pH as well as changes saline soils into alkaline categories. Calcium stabilizes soil, maintains aggregate structure, controls dispersion caused by Na\(^+\), and increases hydraulic conductivity of soil thereby helping in leaching process of saline soils.

Figure 4 indicates that calcium trends were similar as those of sodium but higher values. The calcium leaching from the soil profile is linear being more prominent in highly salt concentrated soil with 6400 ppm salts and less increase under 3200 ppm treatment. In control treatment, the Ca\(^{++}\) trend slightly increased. The analysis of variance of Ca\(^{++}\) behavior in the soil columns is given in Table 3.
Table 3. Analysis of variance on Ca^{++} ion concentration (ppm) in leachate from uniformly packed sandy loam soil columns with different salt concentrations leached with fresh water as a function of time.

<table>
<thead>
<tr>
<th>S.V</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
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<tr>
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<td>350915</td>
<td>0.94 N.S.</td>
</tr>
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<td>151738005</td>
<td>75869020</td>
<td>203.08 ****</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>1494334</td>
<td>373584</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>13</td>
<td>29536586</td>
<td>2272045</td>
<td>216.15 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>26</td>
<td>30412207</td>
<td>1169700</td>
<td>111.28 ****</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>204</td>
<td>2144349</td>
<td>10512</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3 shows that there were nonsignificant differences in replications. Treatments were significantly different. Time was very highly significant, as were time and treatment interactions.

The regression models for three treatments ($T_1, R^2 = 0.77; T_2, R^2 = 0.97; T_3, R^2 = 1.00$) are given as follows:

$Ca^{++}$ (Control) $= 173.4835 - 10.228(T) + 0.9588(T^2)$

$S.E = \pm 13.4655\;\pm 3.84799\;\pm 0.24953$

$Ca^{++}$ (3,200 ppm) $= 192.874 - 12.846(T) + 3.9691(T^2)$

$S.E = \pm 40.4629\;\pm 11.56291\;\pm 0.74983$
Sodium/Calcium ratio in leachate

Sodium and calcium are the major factors in the leaching process of salts and hydraulic conductivity. As the Na⁺/Ca²⁺ ratio increases, calcium content decreases, thereby dispersing the soil particles and destroying the aggregate structure of soil. In high calcium soils, however, the particles are hold tightly, and soil aggregates are maintained. Even in high Ca²⁺ soils, the particles lodge in the pores. Moreover, the movement of solutes is curtailed. If particles do not fill the pores, the hydraulic conductivity is maintained at a constant level.

Figure 5 indicates that in the control, the Na⁺/Ca²⁺ ratio decreased with time and became almost constant after about six hours. Under 3200 and 6400 ppm salt concentrations, the Na⁺/Ca²⁺ ratio increased with time. The analysis of variance of Na⁺/Ca²⁺ ratio as a function of time is given in Table 4.

Table 4 indicates that replications of individual treatments were nonsignificant. Treatments themselves were significantly different from each other. Time revealed a highly significant difference. Moreover, treatment and time interactions were highly significant. As a result, the hydraulic conductivity decreased with respect to time in all treatments. In treatment No. 2 and treatment No. 3, sodium movement showed an increasing trend with time compared to calcium movement. This phenomenon inc-
Table 4. Analysis of variance on Na\(^+\)/Ca\(^{2+}\) ratio in leachate from uniformly packed sandy loam soil columns with different salt concentrations leached with fresh water as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
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<td>14.05</td>
<td>7.03</td>
<td>2.07 N.S.</td>
</tr>
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<td>TRT</td>
<td>2</td>
<td>132.97</td>
<td>66.49</td>
<td>19.62 ***</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>13.56</td>
<td>3.39</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>13</td>
<td>9.22</td>
<td>0.71</td>
<td>3.54 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>26</td>
<td>11.55</td>
<td>0.44</td>
<td>2.22 **</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>78</td>
<td>15.62</td>
<td>0.20</td>
<td>-</td>
</tr>
</tbody>
</table>

increased the Na\(^+\)/Ca\(^{2+}\) ratios more in treatment No. 3.

The regression models for three treatments (T1, \(R^2 = 0.20\); T2, \(R^2 = 0.20\); and T3, \(R^2 = 0.88\)) are given as follows:

\[
\text{Na}^+/\text{Ca}^{2+} \text{ (Control)} = 0.727 - 0.035 (T) + 0.0018 (T^2)
\]

S.E = ± 0.0063 ± 0.0246 ± 0.00159

\[
\text{Na}^+/\text{Ca}^{2+} \text{ (3,200 ppm)} = 2.63 - 0.0055 (T) + 0.002 (T^2)
\]

S.E = ± 0.2454 ± 0.07013 ± 0.00454

\[
\text{Na}^+/\text{Ca}^{2+} \text{ (6,400 ppm)} = 1.935 + 0.031 (T) + 0.009 (T^2)
\]

S.E = ± 0.1687 ± 0.0482 ± 0.00313
**pH of leachate**

One of the outstanding physiological characteristics of the soil solutions is its reaction. The importance of soil reactions have long been recognized (Brady, 1974). Three conditions are possible: acidity, neutrality, and alkalinity. The presence of salts, especially calcium, magnesium, and sodium carbonates, also gives a preponderance of hydroxyl ions over hydrogen ions in the soil solution. Thus, the pH level changes, with respect to salt concentrations and time, are important to study.

Figure 6 indicates that the pH values decreased with time in all treatments. As the concentration of the salts (NaCl and CaCl₂) increased, the pH decreased. Analysis of variance of pH in the leachate with respect to time is given in Table 5.

The analysis of variance of pH (Table 5) shows that the replication differences were nonsignificant, indicating that the replications were alike in individual treatments. The treatment effects were significant. Furthermore, time was very highly significant. The interaction between time and treatment was also highly significant. The regression models for three treatments (T₁, R² = 0.83; T₂, R² = 0.73; and T₃, R² = 0.97) are given as follows:

- **pH (Control) = 7.67897 - 0.03379 (T) - 0.00004 (T²)**
  - S.E = ± 0.0704  ± 0.02011  ± 0.00130

- **pH (19,200 ppm) = 6.602 + 0.0216 (T) - 0.00236 (T²)**
  - S.E = ± 0.0452  ± 0.01292  ± 0.00084

- **pH (38,400 ppm) = 7.065 - 0.1473 (T) + 0.00658 (T²)**
Table 5. Analysis of variance on pH of leachate from uniformly packed sandy loam soil columns with different salt concentrations leached with fresh water as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
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<td>REPS</td>
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<td>5.94</td>
<td>2.97</td>
<td>4.35 N.S.</td>
</tr>
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<td>TRT</td>
<td>2</td>
<td>47.04</td>
<td>23.52</td>
<td>34.50 *</td>
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<tr>
<td>ERR(a)</td>
<td>4</td>
<td>2.73</td>
<td>0.68</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>3</td>
<td>4.55</td>
<td>0.35</td>
<td>10.49 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
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<td>1.96</td>
<td>0.08</td>
<td>2.26 **</td>
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<td>ERR(b)</td>
<td>204</td>
<td>6.80</td>
<td>0.03</td>
<td>-</td>
</tr>
</tbody>
</table>

\[ S.E = \pm 0.0398 \pm 0.01138 \pm 0.00074 \]

**Hydraulic conductivity of soil**

Figure 7 indicates that the K rates decreased with increased salt concentrations in uniformly packed soil. Tables 1, 2, 3, 4, 5, present EC, Ca$$^{++}$$, Na$$^+$$, Na$$^+$/Ca$$^{++}$$, and pH analyses, while Figures 2 through 6 show the graphic presentation of these parameters. From the chemical parameters discussed earlier, one can interpret the K rates and deduce leaching processes and interpret K changes with respect to salt
concentrations and time. It is evident from Figure 7 that the maximum K was observed in the control treatment and next to it ranked 3200 ppm salt concentration and then 6400 ppm salt concentration. This indicates that with increase of salt concentration K decreased. The saturated hydraulic conductivity under all treatments had almost similar trend with time but K values decreased as the salt concentration in the leachate increased.

The steady state flow could be expected under saturated conditions, but it did not practically happen probably because of Na\(^+\) dispersion in T2 and T3 and interference of particles in pore geometry. Chen and Banin (1975) also found that reduction in K of soil leached with NaCl-CaCl\(_2\) solutions of low electrolyte concentration are related to fine particle dispersion and the formation of a more continuous network of these particles at higher SAR values. In this study, the use of tap water with very low salt contents confirms the statement of Chen and Banin (1975) that the percolating water had the effect on K rates with time. Similar results were reported by Emerson and Baker (1973). They found favorable conditions for clay dispersion or migration when a loam or sandy loam soil with low ESP values was leached with dilute solutions. A sharp reduction in the concentration of the soil solution below the threshold concentration occurs.

Accordingly, the clay particles flocculate and a high concentration gradient results between the dilute solutions of the macropores and the more concentrated solution in the micropores inside the aggregates. In any case the K reduction is the result of dispersion of particles and lodging of particles in the pores (Gardner, 1945;
Christiansen, 1947; McNeal and Coleman, 1966; McNeal et al., 1966; Bresler, 1971; Shainberg et al., 1981; Velasco-Molina et al., 1971; Felhendler et al., 1974; Pupisky and Shainberg, 1979; Frenkel et al., 1978). It can be concluded that the salt concentrations were the major factors for K increase with treatment differences and reduction with time due to porosity decrease. Frenkel et al. (1978) assigned K reduction with time to clay content and bulk density. In this experiment, however, the soil was of the same texture and bulk density.

Bresler (1971) reported that the K is affected not only by the intrinsic permeability, but also by the properties of the soil solution, such as fluid density and viscosity, which are also affected by the composition and concentration of solutes. The flow behavior in T2 and T3 treatment conditions in this study were very much in agreement with Bresler (1971) findings suggesting that very high dispersion in T2 and T3 caused increase in K but dilution factor reduced K with time where fluid viscosity and density did not become hinderance in flow of solutes. Passioura (1976) found that the saturated hydraulic conductivity decreased as either the total salt concentration of soil solution decreased or the cationic ratio (Na⁺/Ca++) decreased. He also found that in the reclamation of sodic soils, both leaching of salts and physical ripening are necessary requirements. In this study the physical ripening of soil with salts might not be the problem, because soil was saturated with salts for a long time. The analysis of variance on hydraulic conductivity is given in Table 6.

The analysis of variance of K values (Table 6) indicates that the replication differences were nonsignificant. It also indicates that the three replications were
Table 6. Analysis of variance on hydraulic conductivity of uniformly packed sandy loam soil as a function of soil salt concentration and time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
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<tbody>
<tr>
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<td>0.072</td>
<td>0.036</td>
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<td>TRT</td>
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<td>3.015</td>
<td>1.508</td>
<td>57.86 **</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>0.104</td>
<td>0.026</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>13</td>
<td>1.461</td>
<td>0.133</td>
<td>61.87 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>26</td>
<td>0.558</td>
<td>0.025</td>
<td>11.81 ****</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>66</td>
<td>0.142</td>
<td>0.002</td>
<td>-</td>
</tr>
</tbody>
</table>

similar for individual treatments. But treatment differences were significant and time differences were highly significant. However, the interaction of treatments and time was not significant.

As discussed earlier, the columns for individual treatments were similar in leachate values with respect to time. The treatments and time were highly significant, indicating that there was significant difference in $K$ values with respect to salt concentrations and time being more $K$ for T3 than T2 and the lowest $K$ for T1. We may conclude that increase in salt concentration increased $K$ values. The regression models for three treatments ($T_1$, $R^2 = 0.89$; $T_2$, $R^2 = 0.74$; and $T_3$, $R^2 = 0.52$) are given as follows:
K (Control) = 1.34 + 0.025 (T) - 0.0014 (T²)

S.E. = ± 0.0112 ± 0.00411 ± 0.00031

K (3,200 ppm) = 1.12 + 0.0245 (T) - 0.0015 (T²)

S.E. = ± 0.0161 ± 0.00587 ± 0.00044

K (6,400 ppm) = 0.92 + 0.0086 (T) - 0.0006 (T²)

S.E. = ± 0.0075 ± 0.00276 ± 0.00021
Saturated hydraulic conductivity (K) of sandy loam soil decreased as the concentration of salts increased in the soil profile. The highest K was observed in salt free (control) treatment.

The electrical conductivity of the leachate and the trend of sodium and calcium ions increased with time. However, the cation ratio (Na⁺/Ca++) increased in 6,400 ppm salt concentration columns. In case of 3,200 ppm salt and salt free columns the cation ratio remained constant. The leachate pH decreased with an increase in salt concentration.

It was concluded that under a constant head of 5-cm of fresh water for 18 hours the salts can be leached to lower layers in the soil profile provided the drains are installed at the depth of 100-cm. The downward movement of salts increased the salt concentration in the leachate with respect to time. However, 6,400 ppm salt columns need more time to leach the salts for reclaiming the soil.
REFERENCES


Christiansen, J.E. 1947. Some permeability characteristics of saline and alkali soils.


Shainberg, E.B., and Y. Klausner. 1971. Studies on Na/Ca montmorillonite systems—

weathering on clay dispersion and hydraulic conductivity of sodic soils. Soil

Sisson, J.B., and P.J. Wierenga. 1981. Spatial variability of steady-state infiltration

 techniques of measuring soil hydraulic conductivity. In: Proc. of the Third

Talsma, T., and P.M. Hallam. 1980. Hydraulic conductivity measurements of

Topp, G.C., and Sattlecker. 1983. A rapid measurement of horizontal and vertical
 components of saturated hydraulic conductivity. ASAE Paper No. 79-2515,
 ASAE, St. Joseph, MI.

U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and
 alkali soils. U.S. Salinity Laboratory Handbook 60. United States
 Department of Agriculture, Washington, D.C.

 of different mineralogy in relation to sodium adsorption ratio and

Warrick, A.W., G.J. Mullen, and D.R. Nielsen. 1977. Scaling field-measurement

Young, E.G. 1976. Determination of the variation of hydraulic conductivity with
 depth in drained lands and the design of drainage installation. Agric. Water
 Management 1: 57-66.

Zobeck, T.M., N.R. Fausey, and N.S. Al-Hamdan. 1985. Effect of sample cross-
 sectional area on saturated hydraulic conductivity in two structured clay
Figure 1. A soil column.
Figure 2. Electrical Conductivity (EC, mmhos/cm) of leachate with respect to salt concentrations and time in uniformly packed sandy loam soil columns leached with fresh water.
Figure 3. Sodium ion concentration in leachate with respect to salt concentrations and time in uniformly packed sandy loam soil columns leached with fresh water.
Figure 4. Calcium ion concentration in leachate with respect to salt concentrations and time in uniformly packed sandy loam soil columns leached with fresh water.
Figure 5. Cation ratio (Na/Ca) of leachate with respect to salt concentrations and time in uniformly packed sandy loam soil columns leached with fresh water.
Figure 6. pH of leachates with respect to salt concentrations and time in layered sandy loam soil columns leached with fresh water.
Figure 7. Hydraulic Conductivity (K) of uniformly packed sandy loam soil leached with fresh water with respect to salt concentrations and time.
PAPER 4: EFFECTS OF SALINE IRRIGATION WATER ON THE SATURATED HYDRAULIC CONDUCTIVITY OF SALT SATURATED SANDY LOAM SOIL
A laboratory study was conducted to understand saturated hydraulic conductivity and the mechanics of salt transport in large disturbed soil columns. Nine PVC columns measuring 20-cm in diameter and 115-cm long were filled with thoroughly mixed sandy loam soil sieved through 3.175 mm mesh at a bulk density of 1.37 g/cm$^3$.

Two salt concentrations of 19,200 and 38,400 ppm were maintained in the soil by saturating the soil columns with these salt concentration solutions from bottom of the columns using NaCl and CaCl$_2$ (1:1 ratio by weight). Saturated hydraulic conductivity was measured under a constant head of 6-cm of the same concentration of salts in water. The leachate was collected from the bottom of the columns every hour for a period of 36 hours.

The results of this study showed that high salt concentrations influenced the permeability of soil and increased the hydraulic conductivity. The electrical conductivity of leachate increased with time for about 25 hours and then became almost constant.
INTRODUCTION

Soil permeability is an important factor in soil management, and has been studied extensively. It is well known that the concentration and the composition of the percolating solution have a great influence on the stability and the hydraulic conductivity of the soil (Pupisky and Shainberg, 1979).

It is also generally recognized that the high levels of exchangeable sodium lead to soil structural deterioration, which is accompanied by a reduction in the water movement through the soil profile. There is a lack of quantitative information relating soil characteristics to water transmission properties under saline conditions (Naghshineh-Pour et al., 1970).

It is a common knowledge that the hydraulic conductivity of a saturated soil as measured in the laboratory may vary continuously with time (Allison, 1947; Bodman, 1937; Christiansen, 1944; Fireman and Bodman, 1939; Fireman, 1944; Quirk and Schofield, 1955). Among the factors cited or responsible for this variability are the progressive deterioration of soil aggregation in which cation interaction between soil and the flowing solution may play a part, the effects of the soil microorganisms and changes in volume of the entrapped air.

The concentration of sodium and other ions in irrigation waters alters the permeability of soils by affecting the swelling and dispersion of colloidal soil particles (Gardner, 1945; Gardner et al., 1959; McNeal and Coleman, 1966; Naghshineh-Pour
et al., 1968; Quirk and Schofield, 1955). Sodium in irrigation water increases the sodium on adsorption sites of the soil. Soils with exchangeable sodium equal to around 15 percent or more of their exchangeable capacity and low in soluble salts have been shown to exhibit poor physical properties (U.S. Salinity Laboratory Staff, 1954). This effect is attributed to hydrolysis of the exchangeable sodium, causing the soil colloids to disperse. Sodium-affected soils which contain appreciable quantities of soluble salts tend to remain flocculated unless the salts are leached from the soil. As a result, the dispersing effect of sodium is conditioned by other salts in solution and the presence of dispersible material in the soil.

In the development of present-day methods of reclaiming sodic soils, the major emphasis has been placed upon supplying calcium for exchange with sodium on the soil exchange complex. This is an essential part of the reclamation process. From a practical standpoint, however, the rate of passage of water through the soil to facilitate the exchange is also a prime consideration.

It has been known for many years that the transmission rate of water through sodic soil depends very markedly upon the electrolyte concentration of the water. When sodic soil is leached with a water of low-salt content, the permeability may decrease to a value that practically prevents completion of the reclamation process. By increasing the electrolyte concentration of the water, however, the transmission rate can be materially increased. These effects were demonstrated by Fireman and Bodman (1940), Fireman (1944), Christiansen (1947), and others. Quirk and Schofield (1955) published quantitative data on the effect of electrolyte concentration on soil
permeability, and pointed out the advantages of using high-salt waters for reclamation purposes. The relationships among permeability, electrolyte concentration, and exchangeable sodium obtained by Quirk and Schofield are summarized in a review paper by Reeve (1960). Gardner et al. (1959) showed that the effects of electrolyte concentration also extend to flow in the unsaturated state. If water fails to move into and through the soil, regardless of whether calcium has been added to or is available in the soil, reclamation will obviously not take place. Although gypsum is frequently used as an amendment, because of limited solubility in water, it is not always in many instances, effective in maintaining a high permeability. Highly soluble calcium salts such as CaCl$_2$ may be used to supply calcium at a high electrolyte concentration, but for the most part the high cost of these salts makes this impractical. Since, for most of the acidifying amendments, such as sulfur and sulfuric acid, gypsum is usually the end-product of the reaction, these amendments are subject to the same limitations as gypsum.

The use of waters of poor quality having a high-salt content and a high proportion of sodium for reclamation has been unthinkable in the past. At first thought, such use would seem to be a questionable practice of adding salts to already saline soils. Cation exchange equilibria theory indicates, however, that use of high-salt waters, such as sea water, for replacement of sodium and reclamation of sodic soils may be entirely possible. The principle involved is the so-called "valence-dilution" effect, which has been observed by Gapon (1933), Eaton and Sokoloff (1935), Mattson and Wiklander (1940), Davis (1945), Reitemeier (1946), and Schofield (1947). In a soil-
water system where adsorbed cations are in equilibrium with the cations in solution, the equilibrium condition may or may not, depending upon the valence of the cations involved, be altered by the addition of water to the system. If the cations are of the same valence, no change will occur. But with cations of unequal valence, the adsorbed cation of lower valence tends, upon dilution, to be displaced by solution cations of the higher valence (Reeve and Bower, 1960).

There are differences of opinion as to the cation-exchange equilibrium equation that properly describes this process. The subject was investigated by Krishnamurthy and Overstreet (1949), Erikson (1952), Bolt (1955), and Bower (1959). It has also been shown (Bower, 1959) that a Gapon-type equation is of practical value even in systems containing Mg^{++} and K^{+} as well as Na^{+} and Ca^{++}. In any case, the application of the principle is not dependent upon the complete theoretical description of the mechanisms involved. The empirical relationship developed by Bower (1959) and first published in 1954 (U.S. Salinity Laboratory Staff) serves as a useful means of making application of this principle.

Bower (1959) showed that under equilibrium condition, where the principle cations are Na^{+}, Ca^{++}, and Mg^{++}, the ratio Na^{+}/(Ca^{++} + Mg^{++})^{1/2} of the soil solution is directly related to the exchangeable sodium percentage of the soil. This ratio is commonly called the sodium-adsorption ratio (SAR). The change in the ratio that occurs upon dilution is shown by the following equation:

\[ \text{SAR} = \frac{\text{Na}^+}{(\text{Ca}^{++} + \text{Mg}^{++})^{1/2}} \]

where the cationic concentrations are expressed in millimoles.
By beginning the leaching process with a water of sufficiently high electrolyte content, deterioration of the permeability rate can be prevented. Moreover, the rate at which the concentration is reduced serves as a positive means of control over the leaching rate throughout the reclamation period. The experimental studies reported herein were designed primarily to provide preliminary data as to the validity of the theory upon which this method is based. The main objective of this study was to investigate the effects of percolating high salt water through a sandy loam soil already containing the same amount of salts in soil solution. The K values as related with salt concentrations and time will help in making recommendations for leaching of salts in highly saline soils.
MATERIALS AND METHODS

An experiment was conducted to study the effect of high salt solutions used as leachate through salt concentrated soil. The study was conducted on soil columns in the laboratory.

Large soil columns measuring 115-cm long (100-cm soil profile) and 20-cm internal diameter were used. The density of the soil in all columns was uniformly 1.37 g/cm³. The soil packed in the columns was sandy loam from the bank of the Squaw Creek near Ames.

The columns used in this study were made from PVC pipes of 20-cm diameter. Columns measured 115-cm in length. The column bottoms were prepared from the same PVC pipe sections. Two circular plates were used for constructing the column bottom, one of which was used to drill holes to make it perforated, and other piece was used to pass a leachate tube at the bottom of the column. A 5-cm thick ring was placed in between these plates to be firmly glued to the column pipe. Six horizontal solid tubes of 0.794-cm internal diameter were installed through the walls of column pipes inserting 7.62-cm in the soil. The portions of the tubes inside the walls were perforated by saw cuts and were wrapped with fibre glass screen and cheese cloth for soil solution sampling. The open ends of the tubes in the soil were also covered with the same screen and cheese cloth arrangement. Figure 1 gives the details of the column assembly.
The disturbed soil sieved through 3.175 mm mesh was packed in the columns. Six horizontal piezometers were then installed in the soil through walls of the columns at depth intervals of 15-cm using one-inch diameter perforated tube covered with fiberglass screen and cheese cloth inside the walls, and elbow and flexible tubing outside the wall of the pipes. These piezometers were used for collecting water samples at different depths for confirming salt equilibrium and distribution of salts at different depths of the profile. The soil was first saturated with water containing 19,200 and 38,400 ppm salt concentrations from bottom of the columns maintaining two treatments. The water table was raised from the bottom upward with 1-cm rise in water table each time of one hour. When water reached the top of the columns, the water level was maintained on top of the soil surface for one week. At this stage, it was thought that the soil was uniformly saturated with salts.

Water samples were then collected from piezometers at six depths and analyzed for total soluble salts. It was observed that the salt equilibrium was not attained as desired. Concentrations were higher at the bottom layers than at those of the top section. The saturation process was then reversed. The same salt solutions of 19,200 and 38,400 ppm concentrations were passed through the soil columns from top downward. Hydraulic conductivity measurements were made using constant head of 6-cm and leachate was collected from the bottom every hour passing about two pore volumes of solutions through each column. The process took 36 hours in most columns. Water samples were taken from the piezometers and analyzed for salt concentrations at different depths. The soil columns had very satisfactory salt
equilibrium. Hourly leachates collected from the bottoms of the columns were analyzed for EC, Na\(^+\), Ca\(^{++}\), and pH. The Na\(^+\)/Ca\(^{++}\) ratios were calculated using Na\(^+\) and Ca\(^{++}\) data. The saturated hydraulic conductivity values were calculated from leachate volumes using standard method.
Laboratory K values of sandy loam soil were measured as a function of soil and percolating water electrolyte concentrations and time. The textural class of the soil was sandy loam. The combined effect of Sodium Adsorption Ratio (SAR) and salt concentrations on K changes were measured and interpreted in the light of leachate analyses of electrical conductivity (EC) at 25°C, pH, cations (Na⁺ and Ca²⁺), and cationic ratio (Na⁺/Ca²⁺). The soil solution cationic composition in SAR term is commonly used to describe the cationic composition effect on soil hydraulic conductivity (U.S. Salinity Laboratory Staff, 1954). The SAR values of soil solution for 19,200 and 38,400 ppm were 6.24 and 8.82.

Electrical conductivity of leachate

The EC is the function of total dissolved solids and a measure of soil and water salinity level. The EC is usually recorded at 25°C as a reference unit of measurement. Figure 2 indicates the trends of EC with respect to time for leachate samples collected from two salt treatments described earlier. For treatment No. 1, where salts were added to bring the concentrations of column soil to 19,200 ppm (EC = 30 mmhos/cm), the EC values increased with time. Similarly, in columns with salt concentrations of 38,400 ppm (EC = 60 mmhos/cm) increased EC values were observed in the leachate with time. The analysis of variance on electrical conductivity of leachate is given in
Table 1 shows that there was nonsignificant difference in replications of individual treatments. It also suggests that the replications within a treatment were alike and yielded similar leachate amounts. The treatments of 0, 19,200, and 38,400 ppm were very significantly different. The time was very highly significant. The EC from one time to the other significantly differed. The interactions between time and each treatment were very highly significant. The regression models for three treatments ($T_1$, $R^2 = 0.99$; and $T_2$, $R^2 = 0.99$) are given as follows:

Table 1. Analysis of variance on electrical conductivity of leachate from uniformly packed sandy loam soil columns leached with different salt solution concentrations as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F</th>
<th>S.S.</th>
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<td>18018</td>
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<td>ERR(a)</td>
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<td>173</td>
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<td>-</td>
<td></td>
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<tr>
<td>TIME</td>
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<td>1807</td>
<td>62</td>
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<td>353</td>
<td>12</td>
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<tr>
<td>ERR(b)</td>
<td>116</td>
<td>516</td>
<td>5</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
EC (19,200 ppm) = 18.4067 + 0.77 (T) - 0.0123 (T^2)
S.E = ± 0.4432 ± 0.0333 ± 0.00095

EC (38,400 ppm) = 41.2574 + 1.316 (T) - 0.0226 (T^2)
S.E = ± 0.6161 ± 0.0464 ± 0.00132

Sodium ion concentration in leachate

Sodium (Na⁺) is a monovalent cation which plays an important role in sodium affected soils. Sodium causes dispersion of soil particles, destroys soil structure, and

Table 2. Analysis of variance on Na⁺ ion concentration (ppm) in leachate from uniformly packed sandy loam soil columns leached with different salt concentration solutions as a function of time.

<table>
<thead>
<tr>
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<th>M.S.</th>
<th>F.</th>
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<td>34232480</td>
<td>1180430</td>
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<td>0.52 N.S</td>
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<td>187529</td>
<td>-</td>
</tr>
</tbody>
</table>
reduces hydraulic conductivity of soil due to its dispersing effect.

Figure 3 indicates that the Na⁺ ion leached through soil profile at an increasing rate with time. The Na⁺ concentration in the leachate from the 19,200 ppm and 38,400 ppm showed similar trends of positive linearity but higher values for 38,400 ppm due to higher initial salt concentrations in the soil columns. The hydraulic conductivity increased with increase in Na⁺ concentration in percolating water.

The analysis of variance on Na⁺ concentration in the leachate from uniformly packed sandy loam soil columns already saturated with 19,200 and 38,400 ppm salt concentrations leached with same salt concentration solutions with respect to time is given in Table 2.

Table 2 indicates that replications had nonsignificant difference. Treatments had highly significant differences, indicating that the replications were alike and behaved in the same way in each treatment. Treatments were not alike, however, in showing significant difference. Time was very highly significant. The interaction of time with treatments was nonsignificant showing that Na⁺ movement with respect to time was similar in both treatments.

The regression models for three treatments (\( T_1, R^2 = 0.96; T_2, R^2 = 0.85 \)) are given as follows:

\[
\text{Na}^+ \ (19,200 \text{ ppm}) = 2007.72 + 55.1487 (T) - 0.488 (T^2) \\
\text{S.E} = \pm 83.7002 \quad \pm 6.305718 \quad \pm 0.17992
\]

\[
\text{Na}^+ \ (38,400 \text{ ppm}) = 6087.04 + 72.823 (T) - 0.6294 (T^2) \\
\text{S.E} = \pm 213.3766 \quad \pm 16.07515 \quad \pm 0.45867
\]
Calcium ion concentration in leachate

Calcium (Ca^{++) is a divalent cation. Calcium does not pose any hazardous effect on crop growth. The calcium with different hazardous anions acts differently. Calcium in the form of carbonates and bicarbonates increases soil pH as well as changes saline soils into alkaline categories. Calcium stabilizes soil, maintains aggregate structure, controls dispersion caused by Na^{+}, and increases hydraulic conductivity of soil thereby helping in leaching process of salts.

Figure 4 indicates that calcium trends were similar in both treatments. The

Table 3. Analysis of variance on Ca^{++} ion concentration in leachate from uniformly packed sandy loam soil columns leached with different salt concentration solutions as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>12252245</td>
<td>6126123</td>
<td>4.10 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>1</td>
<td>270906883</td>
<td>270906883</td>
<td>181.19 **</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>2</td>
<td>2990362</td>
<td>1495181</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>29</td>
<td>1318107</td>
<td>454520</td>
<td>4.84 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>29</td>
<td>3081749</td>
<td>106267</td>
<td>1.13 N.S</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>116</td>
<td>10896307</td>
<td>93934</td>
<td>-</td>
</tr>
</tbody>
</table>
calcium leaching from the soil profile was increasing with time. The analysis of variance on Ca\(^{++}\) behavior in the soil columns treated differently is given in Table 3.

Table 3 shows that there were nonsignificant differences in replications of each treatment. But treatments were significantly different. The time was very highly significant. Time and treatment interactions, however, were not significantly different. The regression models for three treatments (T\(_1\), R\(^2\) = 0.98; T\(_2\), R\(^2\) = 0.86) are given as follows:

\[
\text{Ca}^{++} (19,200 \text{ ppm}) = 1930.14 + 34.814 (T) - 0.4437 (T^2)
\]
\[
\text{S.E} = \pm 29.2025 \pm 2.20002 \pm 0.06277
\]

\[
\text{Ca}^{++} (38,400 \text{ ppm}) = 3789.43 + 95.29 (T) - 1.6267 (T^2)
\]
\[
\text{S.E} = \pm 166.9818 \pm 12.5799 \pm 0.35894
\]

**Sodium/Calcium ratio in leachate**

Sodium and calcium are the main components in saline soils that influence the leaching process of salts and hydraulic conductivity of soil. As the Na\(^+\)/Ca\(^{++}\) ratio increases, calcium content decreases and sodium content increases, causing dispersion of the soil particles and destruction of aggregate structure of soil. In high calcium soils the particles stay intact and soil aggregates are maintained. In high Ca\(^{++}\) soils, the particles may lodge in the pores, and the movement of solutes is may reduce. If particles do not fill the pores, the hydraulic conductivity remains constant.

Figure 5 indicates that under 19,200 ppm salt concentration, the cation ratio
increased with time. Below 38,400 ppm salt concentrations, however, the \(\text{Na}^+/\text{Ca}^{++}\) ratio decreased with time for about 18 hours of leaching of salts and then increased with time. The analysis of variance of \(\text{Na}^+/\text{Ca}^{++}\) ratio as a function of time is given in Table 4.

Table 4. Analysis of variance on \(\text{Na}^+/\text{Ca}^{++}\) ratio in leachate from uniformly packed sandy loam soil columns leached with different salt concentration solutions as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>1.11</td>
<td>0.56</td>
<td>1.83 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>1</td>
<td>4.73</td>
<td>4.73</td>
<td>15.58 *</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>2</td>
<td>0.61</td>
<td>0.30</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>29</td>
<td>0.30</td>
<td>0.01</td>
<td>1.10 N.S.</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>29</td>
<td>0.43</td>
<td>0.02</td>
<td>1.57 *</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>116</td>
<td>1.09</td>
<td>0.01</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4 indicates that replications of individual treatments were similar. Treatments were significantly different. Time was nonsignificant. Treatments and time interaction, however, were significantly different. The analysis suggests that the \(\text{Na}^+/\text{Ca}^{++}\) ratios were fluctuating with time. This phenomenon makes the hydraulic
conductivity unstable with respect to time in both treatments. The regression models for three treatments ($T_1, R^2 = 0.84; T_2, R^2 = 0.25$) are given as follows:

$$\text{Na}^+/\text{Ca}^{++} (19,200 \text{ ppm}) = 1.02 + 0.011 (T) - 0.0001 (T^2)$$

$S.E = \pm 0.0318 \pm 0.0024 \pm 0.00007$

$$\text{Na}^+/\text{Ca}^{++} (38,400 \text{ ppm}) = 1.56 - 0.012 (T) + 0.0003 (T^2)$$

$S.E = \pm 0.0511 \pm 0.00385 \pm 0.00011$

**pH of leachate**

One of the main characteristics of the soil solution is its reaction. The importance of soil reaction has long been recognized (Brady, 1974). Three conditions are possible: acidity, neutrality, and alkalinity. The presence of salts, especially calcium, magnesium, and sodium carbonates, also gives a preponderance of hydroxyl ions over hydrogen ions in the soil solution. Thus, pH changes with respect to salt concentrations and time are important to study. Figure 6 indicates that the pH values increased with time in both treatments. As the concentration of the salts (NaCl and CaCl$_2$) increased, the pH increased. Analysis of variance of pH for leachate with respect to time is given in Table 5. The analysis of variance of pH (Table 5) shows that the replication differences were nonsignificant, indicating that the replications were alike. The treatment effects were highly significant and time was very highly significant. The interaction between time and treatment was nonsignificant. The regression models for treatments ($T_1, R^2 = 0.38; T_2, R^2 = 0.50$) are given as follows:
Table 5. Analysis of variance on pH of leachate from uniformly packed sandy loam soil columns leached with different salt concentration solutions as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>0.042</td>
<td>0.021</td>
<td>1.52 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>1</td>
<td>3.267</td>
<td>3.267</td>
<td>235.93 **</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>2</td>
<td>0.028</td>
<td>0.014</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>29</td>
<td>0.931</td>
<td>0.032</td>
<td>10.80 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>29</td>
<td>0.067</td>
<td>0.002</td>
<td>0.77 N.S.</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>116</td>
<td>0.345</td>
<td>0.003</td>
<td>-</td>
</tr>
</tbody>
</table>

\[
\text{pH (19,200 ppm) } = 6.303 + 0.0248 (T) - 0.0004 (T^2)
\]
\[
\text{S.E } = \pm 0.1601 \pm 0.01206 \pm 0.00034
\]
\[
\text{pH (38,400 ppm) } = 6.114 + 0.0188 (T) - 0.0002 (T^2)
\]
\[
\text{S.E } = \pm 0.1160 \pm 0.00874 \pm 0.00025
\]

**Hydraulic conductivity of sandy loam soil**

Figure 7 indicates that the K rates increased with increased salt concentrations in uniformly packed soil. At the same time, K values decreased with time or salt...
concentration increased with time that a reduction of the flow rate of soil solution occurred. Tables 1, 2, 3, 4, 5, present EC, Ca\(^{++}\), Na\(^{+}\), Na\(^{+}/Ca\(^{++}\)), and pH analyses, while figures 2 through 6 show the graphic presentation of these parameters.

It is evident from Figure 7 that the highest K was observed under 38,400 ppm salt concentration treatment and next to it ranked 19,200 ppm salt concentration. The $K_{sat}$ of both treatments showed increasing trend for about 8 hours and then K values decreased with time. It is reasonable to expect a steady-state flow under saturated conditions. This did not in fact occur.

We hypothesize that this is due to Na\(^{+}\) dispersion, a very high salt concentration in leaching solution in both treatments, and the interference of particles in pore geometry with time might have also reduced K values. Chen and Banin (1975) found that reduction in K of soil leached with NaCl-CaCl\(_2\) solutions were related to fine particle dispersion and the formation of a more continuous network of these particles at higher SAR values.

In this study, the use of high salt concentrations confirms the findings of Chen and Banin that the percolating water had the effect on K rates with time. Similar results were reported by Emerson and Baker (1973). They found favorable conditions for clay dispersion or migration when a loam or sandy loam soil was leached with high salt solutions. A sharp increase in the concentration of the soil solution induces dispersion of clay particles. On the other hand, a low concentration gradient occurs between the concentrated solutions of the macropores and the more concentrated solution in the micropores inside the aggregates. In any case, the K reduction is the
result of dispersion of particles and lodging of particles in the pores (Gardner, 1945; Christiansen, 1947; McNeal and Coleman, 1966; McNeal et al., 1966; Bresler, 1971; Shainberg et al., 1981; Velasco-Molina et al., 1971; Felhendler et al., 1974; Pupisky and Shainberg, 1979; Frenkel et al., 1978).

We conclude that the salt concentrations were the major factors for K increase with treatment differences and reduction with time due to porosity decrease. Frenkel et al. (1978) assigned K reduction with time to clay content and bulk density. But in this experiment, the soil was of the same texture and bulk density. Bresler (1971) reported that the K is affected not only by the intrinsic permeability, but also by the properties of the soil solution, such as fluid density and viscosity, which are also affected by the composition and concentration of solutes. The flow behavior under both treatments was very much in agreement with Bresler (1971) findings suggesting that very high dispersion in both treatments caused increase in K proportionally but salt concentration reduced K with time where fluid viscosity and density became hinderance in flow of solutes. Passioura (1976) found that the saturated hydraulic conductivity decreased as either the total salt concentration of soil solution decreased or the cationic ratio (Ca²⁺/Na⁺) increased. He also found that in the reclamation of sodic soils, both leaching of salts and physical ripening are necessary requirements. In this study the physical ripening of soil with salts might not be the problem, because soil was saturated with salts. The analysis of variance of hydraulic conductivity is given in Table 6.

The analysis of variance of K values (Table 6) shows that the replication
Table 6. Analysis of variance on hydraulic conductivity of uniformly packed sandy loam soil leached with different salt concentration solutions as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>11.178</td>
<td>5.589</td>
<td>1.85 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>1</td>
<td>5.836</td>
<td>5.836</td>
<td>1.94 *</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>2</td>
<td>6.027</td>
<td>3.013</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>20</td>
<td>10.971</td>
<td>0.549</td>
<td>13.24 N.S.</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>20</td>
<td>0.657</td>
<td>0.033</td>
<td>0.79 *</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>80</td>
<td>3.314</td>
<td>0.041</td>
<td>-</td>
</tr>
</tbody>
</table>

differences were nonsignificant. It indicates that the three replications were similar for individual treatments. But treatment differences were significant. Time differences were nonsignificant. The interaction of treatments and time was significant. As discussed earlier, the columns for individual treatments were similar in leachate values with respect to time. The treatments were significant indicating that there was significant difference in K values with respect to salt concentrations being more K for T2 than T1. It concludes that increase in salt concentration increased K values. The regression models for three treatments \( (T_1, R^2 = 0.90; T_2, R^2 = 0.95) \) are given as follows:
\[
K (19,200 \text{ ppm}) = 3.214 + 0.0235 (T) - 0.00144 (T^2)
\]

\[
\text{S.E.} = \pm 0.0248 \pm 0.00374 \pm 0.00017
\]

\[
K (38,400 \text{ ppm}) = 3.692 + 0.0077 (T) - 0.0012 (T^2)
\]

\[
\text{S.E.} = \pm 0.0287 \pm 0.00433 \pm 0.00019
\]
Saturated hydraulic conductivity (K) of sandy loam soil increased as the concentration of salts increased in the soil profile. The highest K was observed in 38,400 ppm salt concentration treatment. However, K values decreased with time in all treatments.

The electrical conductivity of the leachate increased with time and so was the trend of sodium and calcium ions. However, cation ratio (Na⁺/Ca++) increased in 19,200 ppm salt concentration columns but decreased for about 20 hours and then increased in 38,400 ppm salt concentration treatment.

It was concluded that under constant head of 6-cm of saline irrigation water for 36 hours the soil permeability can be increased for a soil.
REFERENCES


U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. U.S. Salinity Laboratory Handbook 60. United States Department of Agriculture, Washington, D.C.

Figure 1. A soil column.
Figure 2. Electrical conductivity (EC, mmhos/cm) of leachate with respect to salt concentrations and time in uniformly packed soil columns leached with saline water.
Figure 3. Sodium ion concentration in leachate with respect to salt concentrations and time in uniformly packed soil columns leached with saline water.
Figure 4. Calcium ion concentration in leachate with respect to salt concentrations and time in uniformly packed soil columns leached with saline water.
Figure 5. Cation ratio (Na/Ca) of leachate with respect to salt concentrations and time in uniformly packed soil columns leached with saline water.
Figure 6. pH of leachate with respect to salt concentrations and time in uniformly packed soil columns leached with saline water.
Figure 7. Hydraulic conductivity of uniformly packed sandy loam soil leached with saline water with respect to salt concentrations and time.
PAPER 5: EFFECT OF SALTS ON THE TRANSPORT OF NO$_3$-N AND ATRAZINE THROUGH A SATURATED SOIL PROFILE
A laboratory study was conducted to understand saturated hydraulic conductivity and the mechanics of salt, NO$_3$-N, and atrazine transport in large disturbed soil columns. Nine PVC columns measuring 20-cm in diameter and 115-cm long were filled with thoroughly mixed sandy loam soil sieved through 3.175 mm mesh sieve at a bulk density of 1.40 g/cm$^3$.

Three salt concentrations of 0, 19,200 and 38,400 ppm in the soil were maintained in the soil by saturating the soil columns with these salt concentration solutions from bottom of the columns and then from the top for 36 hours. Two pore volumes of salt solutions were passed through each column. Also, urea- ammonium-nitrate (N) and atrazine at the concentration of 200 mg/L and 2 mg/L, respectively were added in the percolating water. Saturated hydraulic conductivity was measured under a constant head of 6-cm of fresh water. The leachate was collected from the bottom of the columns every hour for a period of 42 hours.

The results of this study showed that salt concentrations influenced the hydraulic conductivity of the soil. The electrical conductivity of leachate decreased with time. The NO$_3$-N and Atrazine movements were also influenced by salt concentrations.
Water soluble salts, nutrients, pesticides, and other agricultural chemicals will move with water in porous media. Different chemicals act differently, however, when they come in contact with soil particles. The same holds, of course, with regard to soil interaction with different chemicals.

The water infiltration characteristics of a soil strongly influence the type and management of salts, pesticides, nitrates, and other water pollutants. Soils with a high concentration of dissolved solids may have reasonable water transmission rates below the soil surface due to release of electrolytes from the soil (Gardner, 1945; Martin and Richards, 1959; Reeve, 1960). Rao and Davidson (1979) found that high pesticide concentrations in groundwater were due to rapid leaching and minimal microbiological decomposition. Little is known, however, about the effects of salts in soil on pesticides or nitrate movement.

In uniformly saturated soil with a constant water application or in pulses of water, as in irrigation, the water content bulges result. Pressures exist in both vertical and horizontal directions (Childs, 1960). When water is applied to the soil, particles of soils with high smectite (montmorillonite) clay content may swell considerably due to hydration of expandable soil minerals (Quirk and Schofield, 1955). Such swelling reduces the cross-sectional area of soil pores that influence chemical movements. The process of swelling is more pronounced in the presence of high Na⁺ or low salt con-
centrations, or both, in the soil water. Thus, saline soils differ in their transmitting characteristics of water and solutes dissolved in it.

Contaminants which enter the subsurface environment may be transported along with the regional flux of water as dissolved constituents. If they are volatile, a significant fraction may diffuse into the vadose zone as part of the soil gas. From here they may also dissolve into the residual soil water retained in the pore structures. This water will be displaced by infiltrating water, eventually reaching the water table and adding to the contamination already there. Contaminants which are heavier than water will pass downward through the aquifer and concentrate at the bottom and add to the return flows (Brannaka and Jarrett, 1990). The chemicals, particularly pesticides (atrazine) and nitrate act in the soil through four major mechanisms: adsorption/desorption of chemicals in respect to soil particles and organic matter that makes pesticides unavailable for leaching; chemical degradation due to microbial and photochemical decomposition; volatilization, leaching, and chemical change. According to Jury (1986), the transport of chemicals is governed by certain physical and chemical properties including solubility, vapor pressure, adsorption rate, and soil reactivity with respect to temperature and other weather conditions. These factors could be summarized as rate of chemical use, method of application, cropping system, irrigation and drainage practices, and chemical compound characteristics. However, soil water content, soil bulk density, soil permeability, clay content, organic matter content, and water holding properties of soil are important governing factors (Smith et al., 1988).

The saturated hydraulic conductivity ($K$) of soils is an important soil property
The saturated hydraulic conductivity (K) of soils is an important soil property needed to predict the flow of water through the soil profile, and for the design of drainage and irrigation systems. The variability and heterogeneity of most field soils affect K values, regardless of the method used for their measurements. The K of a soil not only is a function of the soil texture, but is also dependent on soil structure, salinity levels of soil, and salt composition of soil solution.

It is well documented that the concentration and the composition of the percolating soil solution through the soil profile have a great influence on the stability and the K value of the soil (Pupisky and Shainberg, 1979). McNeal and Coleman (1966) found that increasing the Sodium Adsorption Ratio (SAR) and decreasing the electrolyte concentration of the percolating solution induced a decrease in soil permeability. McNeal et al. (1966) found strong positive correlation between soil swelling, expandable clay content, and the K values. Various investigators (Gardner, 1945; Gardner et al., 1959; McNeal et al., 1966; Shainberg et al., 1981) suggested that the reduction in permeability was due to clogging of conducting pores. They found that when soils of low ESP values were leached with dilute salt solution, swelling was the dominant mechanism at high ESP values. Emerson and Baker (1973) found favorable conditions for clay dispersion or migration when a loam or sandy loam soil, with low ESP values, was leached with dilute solutions. They reported that clay dispersion is favored by sharp reduction in the salt concentration at which the clay particles flocculate and a high salt concentration gradient between the dilute salt solutions of the macropores and the more concentrated solution in the micropores.
in soils with low silt content was more pronounced than in soils with similar ESP and clay mineralogy, but with higher silt content.

Velasco-Molina et al. (1971) found that montmorillonitic soils and micaceous soils disperse more in weak salt solutions at low SAR values than do the kaolinitic-halloysitic soils high in iron oxides. In the absence of electrolytes, soils dispersed in relation to their dominant clay minerals: montmorillo- nitic > halloysitic-kaolinitic > micaceous.

Furthermore, Frenkel et al. (1978) concluded that the sensitivity of soils to excessive exchangeable sodium and low electrolyte concentration increased with clay content and bulk density of soil. They also concluded that although montmorillonitic soils were the most sensitive to sodic conditions, both neutral kaolinitic soils and vermiculitic soils were also sensitive to sodic conditions at low electrolyte concentrations. Soils with exchangeable sodium equal to around 15 percent or more of their exchangeable capacity and low in soluble salts have been shown to exhibit poor physical properties (U.S. Salinity Laboratory Staff, 1954). This effect is attributed to hydrolysis of the exchangeable sodium, causing the soil colloids to disperse.

Sodium affected soils which contain appreciable quantities of soluble salts tend to remain flocculated unless the salts are leached from the soil. It indicates that the dispersing effect of sodium is conditioned by other salts in solution and the presence of dispersible material in the soil. Thus, both swelling and dispersion phenomena are related. Either can reduce the K under proper circumstances.

It is generally recognized that the high levels of exchangeable sodium lead to
soil structural deterioration, which is accompanied by a reduction in the water movement through the soil profile (Naghshineh-Pour et al., 1970). There is a lack of quantitative information relating soil characteristics to water transmission properties under saline conditions.

It is common knowledge that $K$ of a saturated soil as measured in the laboratory may vary continuously with time (Allison, 1947; Bodman, 1937; Christiensen, 1944; Fireman and Bodman, 1939; Fireman, 1944; Quirk and Schofield, 1955). Among the factors considered responsible for the $K$ variation are the progressive deterioration of soil aggregation in which cation interaction between soil and the flowing solution may play a part, the effects of the soil microorganisms and changes in volume of the entrapped air.

The simulated conditions created in the laboratory column studies avoid the influence of horizontal component of $K$ (Topp and Sattlecker, 1983). In well structured field soils, vertical structured cracks, worm-holes, and root channels (macropores) would suggest larger values of vertical $K$ than of horizontal $K$ (Bouma, 1982; Topp and Sattlecker, 1983; Wang et al., 1985). This indicates the need for preferential flow studies and their impact on $K$ values. Zobeck et al. (1985) have shown that vertical $K$ for a soil with macropores varied from 20 to over 100 times that of the soil without macropores. Several other researchers have also demonstrated that $K$ values measured within a single soil series varies by several orders of magnitude (Baker, 1978; Nassenhzadeh-Tabrizi and Skaggs, 1983; Sisson and Wierenga, 1981; Warrick et al., 1977; Young, 1976; Kanwar et al., 1987). Taherian et al. (1976) have
reported that field measurements of K are subject to soil variations that may be larger than the differences between the methods. Thus, laboratory methods seem to be better suited for the study of flow characteristics.

Several methods have been developed over the past 4 years to measure in-situ K values using the single and/or double auger-hole methods, piezometer method, and multiple well technique (Bouwer and Jackson, 1974; Kirkham et al., 1974). Several methods are available to measure K in the absence of water table, such as air-entry permeameter, double-tube method, ring infiltrometer, and well-permeameter methods (Bouwer and Jackson, 1974). Some of these methods have been improved for rapid measurements of K (Carter et al., 1983; Topp and Sattlecker, 1983), and most of these methods have been used with various degrees of success (Backlund et al., 1986; Reynolds and Elrick, 1985). But some of the limitations of these methods include larger water requirement and the need for at least two operators to run the tests (Bouwer and Jackson, 1974). Though recent development of new techniques (Merva, 1979; Talsma and Hallam, 1980; Reynolds and Elrick, 1985) have removed most of these limitations.

Elrick et al. (1984), and Reynolds and Elrick (1985) have developed the Guelph permeameter for in-situ measurement of K. This method measures the steady-state rate of water flow of a shallow, cylindrical well in which a constant depth of water is maintained. In shallow depths soil porosity, structure, organic matter status and permanence of strata buildup are altogether different from the soil below the immediate plowed layer.
The K can be determined by several methods. The falling head and constant head infiltration methods (Klute, 1986) are standardized procedures. Bouma and Dekker (1981) describe a method for measuring the vertical and horizontal saturated hydraulic conductivity of undisturbed soil cores. Zobeck et al. (1985) compared several methods for determining hydraulic conductivity, two of which used large soil columns or blocks.

In the past most laboratory studies were conducted on very thin pads of soil or small soil columns. A thorough review of the literature makes it clear that soil column studies containing the entire profile depth (between the soil surface and subsurface drain to a depth of 100 to 120-cm) have not been conducted. Therefore, simulated profile conditions were created for one-dimensional vertical flow in long soil columns for determining flow patterns needed for predicting salt transport and K under saline conditions. From the review of past and current research efforts in determining the losses and fate of nitrate-nitrogen and pesticides, it was found that no study has been reported in the area of solute transport in saline soils. Realizing the importance of environmental concerns created by the pollution agents such as fertilizers and pesticides used in agriculture, the present study was conducted in the laboratory using large soil columns. The salt effects on the movement of nitrate and atrazine were studied. The main objectives of this study were to investigate the effects of salt concentrations on saturated K of a soil and transport of NO$_3$-N and atrazine using long disturbed homogeneous soil columns.
MATERIALS AND METHODS

Column assembly

The experiments were conducted in the laboratory using large columns of 115-cm length, which were filled with soil representing a uniform soil bulk density of 1.40 g/cm³. The soil used for the experiment was collected from the banks of the Squaw Creek in the NW corner of the city of Ames, Iowa. The textural class of the soil was sandy loam. The soil from a one-meter square area was dug to a depth of one meter and was brought to the laboratory in plastic bags. Soil samples were spread on the floor for air drying. After air drying, the soil was crushed and passed through 3.175 mm mesh sieve and was stored in plastic cans with lids. The soil used for this experiment had some natural salt content (although it will not classify a saline soil). The initial total dissolved solids were at a concentration of 736 ppm.

The columns used in this study were made from PVC pipes of 20-cm diameter, which were cut in lengths of 115-cm for constructing the columns. The column bottoms were prepared from the leftovers of these pipes. Two circular plates were used for constructing the column bottom, one of which was used to drill holes to make it perforated, and other piece was used to pass a leachate tube at the bottom of the column. A 5-cm thick ring was placed in between these plates to be firmly glued to the column pipe. Six horizontal solid tubes of 0.794-cm internal diameter were installed through the walls of column pipes inserting 7.62-cm in the soil. The portions
of the tubes inside the walls were perforated by saw cuts and were wrapped with fibre glass screen and cheese cloth for soil solution sampling. The open ends of the tubes in the soil were also covered with the same screen and cheese cloth arrangement. Figure 1 gives the details of the column assembly.

Taking one column as an experiment unit, in all 9 soil columns were used for three treatments replicated three times. The soil was packed uniformly in the columns by maintaining soil bulk density of 1.40 g/cm³. Salt concentrations of 0, 19,200, and 38,400 ppm were maintained by saturating the soil columns with respective salt concentrations from bottom upwards by raising water table in the increments of 1-cm each time every two hours. After salt solutions reached the top of the columns, the columns were covered with plastic to prevent evaporation and were left for seven days for thorough saturation of the soil with salts and water. Soil solution samples were then taken from horizontal tubes at six depths for salt concentration analysis. From the solution analysis it was determined that the uniform salt concentrations could not be obtained from top to bottom of columns being lower concentrations in top 30-cm. Thus, the same salt solutions for respective treatments were applied from top of the columns at constant head of 6-cm for 36 hours. Soil solution sampling was done as before. The samples were analyzed for salts. Uniform salt concentrations were obtained within acceptable limits. These soil column tops were then covered with plastic sheets, and the present study was conducted after 24 hours. Fresh water with 200 mg/L N in the form of urea ammonium nitrate and 2.0 mg/L atrazine was ponded at constant head of 7-cm on top of the columns. The constant head was maintained
by using a reservoir with control valve and flexible tubes connecting reservoir with the 9 columns. The leachate samples were collected from the bottom of the columns every hour passing 2 pore volumes of water from each column.

**Hydraulic conductivity experiment**

The experiment was conducted to determine the K values for each column of soil by using the constant head method. A constant head was maintained by using a control valve system which maintained a constant water level of 7-cm at the surface of soil at all times.

The leachate was collected at the bottom of the column through a built-in funnel and tubing arrangement (Figure 1). The effluent was collected every hour, and data on effluent volumes (for each time increment) were collected for K calculation. This experiment was conducted for 42 hours. The effluents were analyzed for electrical conductivity (EC), calcium (Ca$$^{++}$$), sodium (Na$$^{+}$$), pH, NO$$₃$$-N and atrazine. Cation ratios (Na$$^{+}$$/Ca$$^{++}$$) were calculated from Na$$^{+}$$ and Ca$$^{++}$$ concentrations data. The K values for the three treatments were calculated by standard method based on Darcy's law. After one pore volume from each column was leached out, soil solution sampling was done from six horizontal tubes (described earlier) in order to analyze nitrate losses at different depths of the profile.
RESULTS AND DISCUSSION

Laboratory K values of sandy loam soil were measured as a function of soil electrolyte concentrations and time. The textural class of the soil was sandy loam. The combined effect of Sodium Adsorption Ratio (SAR) and salt concentrations on K changes were measured and interpreted in the light of leachate analyses of electrical conductivity (EC) at 25°C, pH, cations (Na⁺ and Ca⁺⁺), cationic ratio (Na⁺/Ca⁺⁺), NO₃⁻, N, and atrazine. The soil solution cationic composition in SAR term is commonly used to describe the cationic composition effect on soil hydraulic conductivity (U.S. Salinity Laboratory Staff, 1954). The SAR values of soil solution for 19,200 and 38,400 ppm were 6.24 and 8.82.

Electrical conductivity of leachate

The EC is the function of total dissolved solids and a measure of soil salinity. The EC is usually recorded at 25°C as a reference unit of measurement. Figure 2 indicates the trends of EC with respect to time for leachate samples collected from all three treatments (9 columns). It also indicates that under control treatment, where no additional salts were added to the soil, the EC was almost constant with time, as time progressed the natural salts initially present in the soil profile were leached out and EC showed a slight reduction with time. For treatment No. 2, where salts were added to bring the concentrations of column soil to 19,200 ppm (EC = 30 mmhos/cm), the
EC values decreased with time. Since the amount of solvent (water) infiltrated at an increased rate through the columns as compared to treatment No. 1, resulted in increased K values. Similarly, in columns with an initial concentration of 38,400 ppm decreased EC, Na⁺, Ca²⁺ were observed in the leachate with time. The analysis of variance on electrical conductivity (mmhos/cm) of leachate from uniformly packed sandy loam soil columns saturated with different salt concentrations leached with fresh water as a function of time.

Table 1. Analysis of variance on electrical conductivity (mmhos/cm) of leachate from uniformly packed sandy loam soil columns saturated with different salt concentrations leached with fresh water as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>2950</td>
<td>1475</td>
<td>3.70 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>15095</td>
<td>7547</td>
<td>18.95 *</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>1593</td>
<td>398</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>36</td>
<td>9604</td>
<td>267</td>
<td>95.90 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>67</td>
<td>5706</td>
<td>85</td>
<td>30.61 ****</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>524</td>
<td>1458</td>
<td>3</td>
<td>-</td>
</tr>
</tbody>
</table>

variance on electrical conductivity is given in Table 1.

Table 1 shows that there was nonsignificant difference in replications. This suggests that the replications within a treatment were alike and yielded similar leachate amounts. The treatments of 0, 19,200, and 38,400 ppm were significantly
different at 5% level of probability, the time was highly significant. The EC from one
time to the other significantly differed. Also the interaction between time and
treatment was also very highly significant. The regression models for three treatments
\( (T_1, R^2 = 0.97; T_2, R^2 = 0.98; \text{ and } T_3, R^2 = 0.94) \) are given as follows:

\[
\text{EC (Control)} = 1.6005 - 0.0385 (T) + 0.00069 (T^2) \\
\text{S.E} = \pm 0.0262 \quad \pm 0.00207 \quad \pm 0.00006
\]

\[
\text{EC (19,200 ppm)} = 21.1575 - 0.9382 (T) + 0.01438 (T^2) \\
\text{S.E} = \pm 0.6244 \quad \pm 0.04931 \quad \pm 0.00145
\]

\[
\text{EC (38,400 ppm)} = 32.2608 - 2.0293 (T) + 0.04001 (T^2) \\
\text{S.E} = \pm 1.8633 \quad \pm 0.14716 \quad \pm 0.00433
\]

**Sodium ion concentration in leachate**

Sodium (\( \text{Na}^+ \)) is a monovalent cation, which plays a major role in saline and
sodic soils. Sodium causes dispersion of soil particles, deteriorates soil structure, and
reduces hydraulic conductivity of soil due to its dispersing effect.

Figure 3 indicates that the \( \text{Na}^+ \) ion leached through soil profile at a decreasing
rate with time. The \( \text{Na}^+ \) concentration in the leachate from the 19,200 ppm and
38,400 ppm show similar trends of negative linearity but higher values for 38,400
ppm. In the control, moreover, the \( \text{Na}^+ \) in the leachate from the columns was almost
constant. The hydraulic conductivity decreased with increase in \( \text{Na}^+ \) concentration
in leaching soil solution. The analysis of variance on \( \text{Na}^+ \) concentration in the
leachate from movement through the soil three treatments is given in Table 2.

Table 2 shows that replications had nonsignificant difference. Moreover, treatments showed significant differences, indicating that the replications were alike and behaved in the same way in each treatment. Treatments were not alike and

Table 2. Analysis of variance of Na$^+$ ion concentration in leachate from uniformly packed sandy loam soil columns saturated with different salt concentrations and leached with fresh water as a function of time.

<table>
<thead>
<tr>
<th>S.V</th>
<th>D.F</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>53112432</td>
<td>26556216</td>
<td>2.60 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>267636732</td>
<td>133818366</td>
<td>13.10 *</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>40867599</td>
<td>10216910</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>36</td>
<td>166722188</td>
<td>4631172</td>
<td>48.44 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>67</td>
<td>111097558</td>
<td>1658173</td>
<td>17.34 ****</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>524</td>
<td>50098256</td>
<td>95607</td>
<td>-</td>
</tr>
</tbody>
</table>

showed significant difference. Time and interaction of time with treatments were very highly significant showing that Na$^+$ movement with respect to time was different for each treatment as well as the interaction of time and treatment was also significantly different for each treatment and each time interval. The regression models for three
treatments \( T_1, R^2 = 0.88; T_2, R^2 = 0.98; T_3, R^2 = 0.98 \) are given as follows:

\[
\text{Na}^+ \text{ (control)} = 161.188 - 5.8611 \, (T) + 0.1411 \, (T^2)
\]

\[
\text{S.E} = \pm 5.9702 \pm 0.47149 \pm 0.01386
\]

\[
\text{Na}^+ \text{ (19,200 ppm)} = 2540.92 - 114.237 \, (T) + 1.785 \, (T^2)
\]

\[
\text{S.E} = 86.7955 \pm 6.85468 \pm 0.20152
\]

\[
\text{Na}^+ \text{ (38,400 ppm)} = 4199.72 - 264.147 \, (T) + 5.137 \, (T^2)
\]

\[
\text{S.E} = 131.7668 \pm 10.40629 \pm 0.30594
\]

**Calcium ion concentration in leachate**

Calcium \((\text{Ca}^{++})\) is a divalent cation. Iowa soils are calcareous in nature and calcium is a predominant ion in the soil. Calcium does not pose any hazardous effect on crop growth. The calcium with different anions act differently. Calcium in chemical compounds of carbonates and bicarbonates increases soil pH as well as changes saline soils into alkaline categories. Calcium stabilizes soil, however, maintains aggregate structure, controls dispersion caused by \(\text{Na}^+\), and increases hydraulic conductivity of soil thereby helping in leaching process of saline soils.

Figure 4 indicates that unlike \(\text{Na}^+\), calcium trends were similar. The calcium leaching from the soil profile is negatively linear being more prominent in highly salt concentrated soil \((38,400 \text{ ppm})\) and less linearly but decreasing trend under 19,200 ppm treatment. In control treatment, the \(\text{Ca}^{++}\) trend was almost constant with a slight decrease with time. The analysis of variance of \(\text{Ca}^{++}\) behavior in the soil columns is
given in Table 3.

Table 3 shows that there were nonsignificant differences in replications. Treatments were significantly different. Furthermore, time was very highly significant, as were time and treatment interactions. The regression models for three treatments

Table 3. Analysis of variance on Ca$^{++}$ ion concentration in leachate from uniformly packed sandy loam soil columns saturated with different salt concentrations and leached with fresh water as a function of time.

<table>
<thead>
<tr>
<th>S.V</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>21307547</td>
<td>10653773</td>
<td>3.86 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>78150995</td>
<td>39075497</td>
<td>14.16 *</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>11040408</td>
<td>2760102</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>36</td>
<td>94802677</td>
<td>2633408</td>
<td>63.19 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>67</td>
<td>51509547</td>
<td>768799</td>
<td>18.45 ****</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>524</td>
<td>21838431</td>
<td>41676</td>
<td>-</td>
</tr>
</tbody>
</table>

$(T_1, R^2 = 0.77; T_2, R^2 = 0.96; T_3, R^2 = 0.92)$ are given as follows:

$\text{Ca}^{++} (\text{Control}) = 281.116 - 5.6485 (T) + 0.0601 (T^2)$

S.E = $\pm 19.6125$ $\pm 1.54890$ $\pm 0.04554$

$\text{Ca}^{++} (19,200 \text{ ppm}) = 2012.301 - 105.02 (T) + 1.794 (T^2)$
Sodium/Calcium ratio in leachate

Sodium and calcium are the major players in the leaching process of salts and hydraulic conductivity. As the Na⁺/Ca⁺⁺ ratio increases, calcium content decreases, thereby dispersing the soil particles destroying aggregate structure of soil. In high calcium soils, however, the particles are held tightly and soil aggregates are maintained. Even in high Ca⁺⁺ soils, the particles lodge in the pores, and the movement of solutes is hindered. If particles do not fill the pores, the hydraulic conductivity is maintained constant.

Figure 5 indicates that in control, the Na⁺/Ca⁺⁺ ratio increased with time. In 19,200 and 38,400 ppm, the Na⁺/Ca⁺⁺ ratio increased with time more linearly in treatment No. 2 and almost constant in treatment No. 3. The analysis of variance of Na⁺/Ca⁺⁺ ratio as a function of time is given in Table 4.

Table 4 indicates that replications and treatments showed nonsignificant difference. Also time and interaction of treatment and time were nonsignificant. The analysis suggests that the Na⁺/Ca⁺⁺ ratios were fluctuating giving only a better trend of increase for Control. This phenomenon results in a decrease in hydraulic conductivity with respect to time in all treatments. In all treatments sodium ion movement
Table 4. Analysis of variance on Na⁺/Ca⁺⁺ ratio in leachate from uniformly packed sandy loam soil columns saturated with different salt concentrations and leached with fresh water as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>1.29</td>
<td>0.65</td>
<td>0.28 NS</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>64.69</td>
<td>32.35</td>
<td>13.91 NS</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>9.30</td>
<td>2.33</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>31</td>
<td>2.57</td>
<td>0.08</td>
<td>0.70 NS</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>62</td>
<td>4.90</td>
<td>0.08</td>
<td>0.67 NS</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>186</td>
<td>21.85</td>
<td>0.12</td>
<td>-</td>
</tr>
</tbody>
</table>

showed increasing trend and Ca⁺⁺ was almost maintaining proportion with Na⁺. The regression models for three treatments (T1, R² = 0.51; T2, R² = 0.30; and T3, R² = 0.10) are given as follows:

\[
\text{Na⁺/Ca⁺⁺ (Control)} = 0.598 - 0.016 (T) + 0.00061 (T^2)
\]

S.E = ± 0.0646 ± 0.00510 ± 0.00015

\[
\text{Na⁺/Ca⁺⁺ (19,200 ppm)} = 1.23 + 0.021 (T) - 0.0003 (T^2)
\]

S.E = ± 0.1623 ± 0.01282 ± 0.00038

\[
\text{Na⁺/Ca⁺⁺ (38,400 ppm)} = 1.58 + 0.010 (T) - 0.0004 (T^2)
\]

S.E = ± 0.1409 ± 0.01113 ± 0.00033
pH of leachate

One of the outstanding physiological characteristics of the soil solutions is its reaction. The importance of soil reaction have long been recognized (Brady, 1974). Three conditions are possible: acidity, neutrality, and alkalinity. The presence of salts, especially calcium, magnesium, and sodium carbonates, also gives a preponderance of hydroxyl ions over hydrogen ions in the soil solution. Thus, pH changes with respect to salt concentrations and time are important to study.

Figure 6 indicates that the pH values increased with time in all treatments. As the concentration of the salts (NaCl and CaCl₂) decreases, the pH increases. Analysis of variance of pH trends for leachate with respect to time is given in Table 5.

The analysis of variance of pH (Table 5) shows that the replication differences were nonsignificant indicating that the replications were alike. The treatment effects were significant at 5% level and time was very highly significant. The interaction between time and treatment was also very highly significant. The regression models for three treatments (T₁, R² = 0.23; T₂, R² = 0.26; and T₃, R² = 0.91) are given as follows:

pH (Control) = 8.144 - 0.0003 (T) + 0.00014 (T²)
S.E = ± 0.0825 ± 0.00651 ± 0.00019

pH (19,200 ppm) = 7.853 + 0.0079 (T) + 0.000052 (T²)
S.E = ± 0.1570 ± 0.01240 ± 0.00036

pH (38,400 ppm) = 7.595 + 0.0301 (T) - 0.0005 (T²)
Table 5. Analysis of variance on pH of leachate from uniformly packed sandy loam soil columns saturated with different salt concentrations and leached with fresh water as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>0.818</td>
<td>0.409</td>
<td>1.03  N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>13.608</td>
<td>6.804</td>
<td>17.20 *</td>
</tr>
<tr>
<td>ERR (a)</td>
<td>4</td>
<td>1.583</td>
<td>0.396</td>
<td>-</td>
</tr>
<tr>
<td>Time</td>
<td>6</td>
<td>6.291</td>
<td>0.175</td>
<td>4.01 ****</td>
</tr>
<tr>
<td>TRT*Time</td>
<td>67</td>
<td>7.114</td>
<td>0.106</td>
<td>2.44 ****</td>
</tr>
<tr>
<td>ERR (b)</td>
<td>524</td>
<td>22.832</td>
<td>0.044</td>
<td>-</td>
</tr>
</tbody>
</table>

S.E = ± 0.0443 ± 0.00350 ± 0.00010

Saturated hydraulic conductivity of salt saturated soil

Figure 7 indicates that the K rates increased with increased salt concentrations in uniformly packed soil. Tables 1, 2, 3, 4, 5, present EC, Ca**, Na*, Na*/Ca**, and pH analyses, while Figures 2 through 6 show the graphic presentation of these parameters. From the chemical parameters discussed earlier, one can interpret the K rates thoroughly and deduce leaching processes and calculate K values.
It is evident from Figure 7 that the maximum K was observed in 38,400 ppm and next to it ranked 19,200 ppm salt concentration and then control with no salts added. The K of all treatments was almost constant with time. Treatment No. 2, however, had a consistent pattern and treatment No. 3 had the highest K values. The steady state flow is reasonably be expected under saturated conditions. It did not practically happen probably because of Na\(^+\) dispersion in T2 and T3 and the interference of particles in pore geometry.

Chen and Banin (1975) also found that reduction in K of soil leached with NaCl-CaCl\(_2\) solutions of low electrolyte concentration are related to fine particle dispersion and the formation of a more continuous network of these particles at higher SAR values. In this study, the use of tap water with very low salt contents confirms the findings of Chen and Banin (1975) to the effect that the percolating water reduced rates over time. Similar results were reported by Emerson and Baker (1973). They found favorable conditions for clay dispersion or particle migration when a loam or sandy loam soil with low ESP values was leached with dilute solutions. Accordingly, a sharp reduction in the concentration of the soil solution below the threshold concentration occurred. At this concentration the clay particles flocculate and a high concentration gradient occurs between the dilute solutions of the macropores and the more concentrated solution in the micropores inside the aggregates.

In case the K reduction is the result of particle dispersion and lodging of particles in the pores (Gardner, 1945; Christiansen, 1947; McNeal and Coleman, 1966; McNeal et al., 1966; Bresler, 1971; Shainberg et al., 1981; Velasco-Molina et al., 1971;
Felhendler et al., 1974; Pupisky and Shainberg, 1979; Frenkel et al., 1978). We may conclude that the salt concentrations were the major factors for K increase with treatment differences and reduction with time due to porosity decrease. Frenkel et al. (1978) assigned K reduction with time to clay content and bulk density. In this experiment, however, the soil was of the same texture and bulk density. Bresler (1971) reported that the K is affected not only by the intrinsic permeability but also by the properties of the soil solution, such as fluid density and viscosity, which are in turn affected by the composition and concentration of solutes. The flow behavior in T2 and T3 treatment conditions in this study are very much in agreement with Bresler (1971) findings suggesting that very high dispersion in T2 and T3 caused increase in K but dilution factor reduced K with time where fluid viscosity and density did not become hinderance in flow of solutes. Passioura (1976) found that the saturated hydraulic conductivity decreased as either the total salt concentration of soil solution decreased or the cationic ratio (Na⁺/Ca++) decreased. He also found that in the reclamation of sodic soils, both leaching of salts and physical ripening are necessary requirements. In this study the physical ripening of soil with salts might not be the problem, because soil was saturated with salts for a long time. The analysis of variance on hydraulic conductivity is given in Table 6.

The analysis of variance of K values (Table 6) shows that the replication differences were nonsignificant. It indicates that the three replications were similar for individual treatments. However, treatment differences were significant. Time differences were very highly significant. The interactions of treatment and time were
Table 6. Analysis of variance on saturated hydraulic conductivity of uniformly packed sandy loam soil saturated with different salt concentrations and leached with fresh water as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>1.05</td>
<td>0.52</td>
<td>1.05 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>10.64</td>
<td>5.32</td>
<td>10.62 *</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>2.00</td>
<td>0.50</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>26</td>
<td>6.21</td>
<td>0.24</td>
<td>7.42 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>41</td>
<td>1.11</td>
<td>0.03</td>
<td>0.84 N.S.</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>134</td>
<td>4.32</td>
<td>0.03</td>
<td>-</td>
</tr>
</tbody>
</table>

not significant. It concludes that increase in salt concentration increased K values. The regression models for three treatments ($T_1$, $R^2 = 0.96$; $T_2$, $R^2 = 0.98$; and $T_3$, $R^2 = 0.98$) are given as follows:

$K$ (Control) = $2.401 - 0.008 (T) - 0.00013 (T^2)$

S.E. = ± 0.0211 ± 0.00216 ± 0.00007

$K$ (19,200 ppm) = $2.704 - 0.0041 (T) - 0.00029 (T^2)$

S.E. = ± 0.0130 ± 0.00133 ± 0.00005

$K$ (38,400 ppm) = $3.351 - 0.0204 (T) - 0.00031 (T^2)$

S.E. = ± 0.0132 ± 0.00135 ± 0.00005
NO₃⁻N losses at different depths of soil profiles

Figures 9, 10, and 11 show nitrate losses at different depths of soil profiles as influenced by three salt concentrations of 0, 19,200, and 38,400 ppm in the soil. It was observed that in all salt treatments the nitrate concentration decreased with depth.

Table 7. Analysis of variance on NO₃⁻N (ppm) collected at different depths of uniformly packed sandy loam soil profiles saturated with different salt concentrations as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REP</td>
<td>2</td>
<td>32872</td>
<td>16436</td>
<td>2.30 N.S.</td>
</tr>
<tr>
<td>TRT</td>
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<td>9507</td>
<td>4754</td>
<td>0.67 N.S.</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>28578</td>
<td>7144</td>
<td>-</td>
</tr>
<tr>
<td>DEPTH</td>
<td>5</td>
<td>86080</td>
<td>17216</td>
<td>10.78 ****</td>
</tr>
<tr>
<td>TRT*DEPTH</td>
<td>10</td>
<td>12836</td>
<td>1284</td>
<td>0.80 N.S.</td>
</tr>
<tr>
<td>REP<em>TRT</em>DEPTH</td>
<td>30</td>
<td>47907</td>
<td>1597</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>5</td>
<td>1249</td>
<td>2499</td>
<td>17.91 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>10</td>
<td>4754</td>
<td>475</td>
<td>3.41 ****</td>
</tr>
<tr>
<td>DEPTH*TIME</td>
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<td>4217</td>
<td>169</td>
<td>1.21 N.S.</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>230</td>
<td>32091</td>
<td>140</td>
<td>-</td>
</tr>
</tbody>
</table>
of the soil profile. The nitrate concentrations increased with time, however, at all six depths of the profile. The movement of nitrate at each depth for control treatment was the lowest, the highest being for 38.400 ppm salt concentration at each depth and almost at each time. Table 7 gives the analysis of variance on nitrate data collected from various depths of soil profile.

Table 7 indicates that there was no significant effect of replications and treatments. Profile depths were very highly significant. Treatment and depth interactions were nonsignificant. Time was very highly significant and so were the interactions of treatment and time.

NO$_3$-N movement from bottom of soil profiles

The evidence available to us indicates that nitrate moves with water through the soil profile as a solute. MacKenzie and Viets (1974) and Merva and Belcher (1990) reported that soluble nutrients and other chemicals applied to or contained in the soil may leach from the soil profile. Loudon et al. (1986) found leaching of nutrients from the soil by percolating water. According to these authors, the rate of concentration depended on tillage methods. The soil used for this study was a disturbed soil that represented plowed conditions. The depth to which chemicals move in soils depends in a complex way upon a number of factors including soil pH, bulk density, moisture content, and soil organic-carbon, chemical, and weather factors (Nofziger and Hornsby, 1986; Smith et al., 1988). Very little is known, however, about the effects
of salts on solute transport in the soil. Harmsen and van Schrevan (1955) stated that the mineralization and immobilization of nitrogen is usually a microbial process and is much influenced by soil conditions.

Laura (1974), Bandyopadhyay and Bandyopadhyay (1983), Singh and Rai (1975), and Gandhi and Paliwal (1976) found that the decomposition rate of organic matter and mineralization rate of nitrogen decreased due to increase in salinity. Furthermore, according to MacKenzie and Viets (1974), soluble nutrients and other chemicals applied to or contained in the soil may be dissolved by water and leached from the soil profile. At the same time, some materials will be removed from solution by adsorption and the formation of precipitates. The composition of leachate may also depend on the aeration status of the soil.

Water continuously flowing through a saturated profile may have a different composition. Nitrate-nitrogen movement greatly reduced in moderately well-drained soils because of reduction in effluent volume (Gillium et al., 1979). Schwab et al. (1980), Bottcher et al. (1981), and Schwab and Logan (1982) reported nitrate-nitrogen loss in subsurface drains.

Apparently the NO$_3^{-}$-N concentration decreased with depth of profile. Bengtson (1991) reported that subsurface drainage reduced nutrient loss by substantial amount. Kanwar et al. (1985) found more nitrate-nitrogen in no-till soils compared to tilled soil suggesting that disturbed soil might allow more nitrate to leach. Figure 8 further depicts that the nitrate concentration reduced linearly in control treatment compared to the other two treatments signifying that salt concentrations induced more nitrate
to leach deeper. Figure 9 indicates that nitrate movement through soil profile increases with time, the highest losses being in 38,400 ppm salt concentrations. As the soil EC reduced in dispersed soil, the nitrate movement increased. Analysis of variance on NO₃-N concentration collected from the column bottoms is given in Table 8.

Table 8. Analysis of variance of NO₃-N (ppm) collected from bottom of uniformly packed sandy loam soil columns saturated with different salt concentrations as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REP</td>
<td>2</td>
<td>4349</td>
<td>2175</td>
<td>3.31  N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>2707</td>
<td>1354</td>
<td>2.06  N.S.</td>
</tr>
<tr>
<td>ERR(a)</td>
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<td>2631</td>
<td>658</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>8</td>
<td>38585</td>
<td>4823</td>
<td>55.74 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>16</td>
<td>2214</td>
<td>138</td>
<td>1.60  N.S.</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>48</td>
<td>4153</td>
<td>87</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 8 indicates that the replications and treatments had nonsignificant differences. Time, however, was very highly significant. The highest nitrate concentration was detected in T3 in which the highest salt concentration was applied. The interaction of treatments and time were also nonsignificant.
Atrazine movement from bottom of soil profiles

Baker and Johnson (1979) reported that pesticides remain concentrated in top 5-cm of soil under field conditions. It suggests that atrazine is a slow moving chemical in the profile. Cohen et al. (1984) reported, however, that the agricultural pesticides have proven to be groundwater contaminants. Cohen et al. (1986) detected 0.3-3.0 ug/L atrazine at a residue range and they reported atrazine contamination in groundwater in 5 states. Isensee et al. (1988) recorded atrazine concentration of 0.2-1.8 ppb in shallow groundwater.

These studies conclude that atrazine leaches through the soil. Donigian and Rao (1986), however, explained that the uptake, translocation, accumulation, and transformation of pesticides by plants affect the availability of pesticides for transport processes. They argue that plant processes can serve as both a sink and a source of pesticides residues available for transport.

In the present study no plants were growing on the column soil. Thus, plant interference in atrazine was not detected. The single determinant of atrazine movement in this study were soil properties and salt concentrations where the soil was uniformly the same in all treatments. Thus, the salts concentrations were the determinant of atrazine movement patterns.

According to Jury (1986), Nofziger and Hornsby (1986), and Smith et al. (1988) the factors that influence the transport of chemicals in porous media are solubility, vapor pressure, adsorption rate, soil reactivity, environmental, and management
conditions. Soil organic carbon content and partition coefficient and degradation of chemicals also influence pesticide movement in the soil. No research work has been reported in the past that could provide evidence of salt effect on atrazine movement in the soil. Analysis of variance on atrazine concentration from column bottoms is given in Table 9.

Table 9 indicates that there were no significant differences in replications, treatments, and interaction of treatments and time. Time, however, had a highly significant difference.

Table 9. Analysis of variance on atrazine concentration (ppb) from bottom of uniformly packed sandy loam soil columns saturated with different salt concentrations as a function of time.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REP</td>
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<td>2575352</td>
<td>1287676</td>
<td>3.92 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>2</td>
<td>945445</td>
<td>472723</td>
<td>1.44 N.S.</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>4</td>
<td>1312569</td>
<td>328142</td>
<td>-</td>
</tr>
<tr>
<td>TIME</td>
<td>4</td>
<td>3724426</td>
<td>931107</td>
<td>16.12 ****</td>
</tr>
<tr>
<td>TRT*TIME</td>
<td>8</td>
<td>709155</td>
<td>88644</td>
<td>1.53 N.S.</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>24</td>
<td>1386471</td>
<td>57770</td>
<td>-</td>
</tr>
</tbody>
</table>
Saturated hydraulic conductivity (K) of sandy loam soil increased as the concentration of salts increased in the soil profile. The highest K was observed in 38,400 ppm salt concentration treatment. However, K values decreased with time in all treatments.

The electrical conductivity of the leachate and the trend of sodium and calcium ions decreased with time. The cation ratio (Na\(^+\)/Ca\(^{++}\)) was almost constant for 38,400 ppm salt concentration, however, it increased with time in the other two treatments. The pH of the leachate increased with a decrease in salt concentration. The NO\(_3\)-N concentration increased with time at all depths of the profile but decrease with depth in all treatments. However, the highest loss of NO\(_3\)-N was in 38,400 ppm salt concentration soil columns at almost all depths. The loss of NO\(_3\)-N from the bottom of the columns had a similar trend at different depths. The atrazine concentration in the leachate from column bottoms increased with increase in soil salt concentration. Also, atrazine loss increased with time in all treatments.
REFERENCES


U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. U.S. Salinity Laboratory Handbook 60. United States Department of Agriculture, Washington, D.C.


Figure 1. A soil column.
Figure 2. A soil column with piezometers.
Figure 3. Electrical conductivity (EC, mmhos/cm) of leachate with respect to salt concentrations and time in uniformly packed soil columns leached with fresh water.
Figure 4. Sodium ion concentration in leachate with respect to salt concentrations and time in uniformly packed soil columns leached with fresh water.
Figure 5. Calcium ion concentration in leachate with respect to salt concentrations and time in uniformly packed soil columns leached with fresh water.
Figure 6. Cation (Na/Ca) ratio of leachate with respect to salt concentrations and time in uniformly packed soil columns leached with fresh water.
Figure 7. pH of leachate with respect to salt concentrations and time in uniformly packed soil columns leached with fresh water.
Figure 8. Hydraulic conductivity of uniformly packed sandy loam soil leached with fresh water as a function of salt concentrations and time.
Figure 9. Relative NO$_3$-N concentration versus pore volume at different soil profile depths at zero concentration of salts in soil columns.
Figure 10. Relative NO$_3$-N concentration versus pore volume at different soil profile depths at 19,200 ppm concentration of salts in soil columns.
Figure 11. Relative $\text{NO}_x\text{-N}$ concentration versus pore volume at different soil profile depths at 38,400 ppm concentration of salts in soil columns.
Figure 12. Relative NO$_3$-N concentration in leachate collected at the bottom of the uniformly packed sandy loam soil columns.
Figure 13. Relative concentration of atrazine in leachate collected at the bottom of the uniformly packed sandy loam soil columns.
PAPER 6: EFFECTS OF WATER-TABLE DEPTHS ON SALTS AND NITROGEN MANAGEMENT
A laboratory study was conducted to investigate the effects of two water table depths (30 and 60-cm) on the leaching of salts and NO₃-N in disturbed soil columns. Twelve PVC columns measuring 20-cm in diameter and 45 and 75-cm long were filled with two types of soil (sandy loam and nicollet loam) mixed and sieved through 3.175 mm sieve at bulk densities of 1.40 and 1.25, respectively. A salt concentration of 6400 ppm (10 mmohs/cm) was maintained in the soil by mixing NaCl and CaCl₂. The soil columns were saturated from the bottom by raising the water table.

Four irrigations of 1.20 liters each were applied at an interval of 10 days. Nitrogen fertilizer in the form of urea ammonium nitrate at the concentration of 200 mg/L was added to irrigation water each time. After every irrigation, drain effluents and water table samples were collected. Soil samples were taken from three depth increments (10, 20, and 30-cm and 20, 40, and 60-cm from 30 and 60-cm long soil columns, respectively), three times at an interval of 15 days. First soil sampling was done after 72 hours of fourth irrigation.

The results of this study showed significant effects of soil type and depth of water table on the movement of nitrate-nitrogen and salt leaching. The water table salt concentration increased as irrigations progressed and salts leached to lower layers of the columns. A very significant upward movement of salts was also recorded in soil profiles.
When surface irrigation is applied, water may run off, infiltrate, or evaporate from the surface layers. If the water moves deeper, it may reach the root zone and be taken up by the plant roots. If the irrigation water had entered a saturated soil, it might move under gravity down past the root zone to the water table. If the root zone is taken as a reference point, then water can move into it not only from above but also from below. As the upper soil layers dry out, a negative pressure results in capillary movement of water from the water table to overlying soil layers. If the water table is very close to the root zone, very small decreases in water potential around the roots will suck water upward, and the roots will be constantly bathed by this liquid from below.

It is extremely important that at any point, while in the liquid state, water may be carrying dissolved salts. Moreover, if water evaporated from the salt water mixture, the remaining salts will be more concentrated. It is this concentration increase that results in a soil salinity problem. However, the process may work in the other direction. Water entering the soil may dissolve soil salts and carry them along through the soil down past the root zone. For any given salt concentration of applied water, there is some volume of water that is great enough to carry all the salts down through the root zone even after losses through evapotranspiration. This process is known as leaching, it is fundamental to both soil salinity prevention and reclamation.
Salinity may therefore be understood by reference to soils and their water conducting properties, climate, soil drainage and the water table. In effect, the salt budget is a consequence of the irrigation water budget. Shifts in water are usually accompanied by shifts in salts.

The goals of an irrigator are two-fold. He must supply enough water for plant consumption (evapotranspiration) and enough additional water for the leaching of salts past the root zone. Balanced against these supply requirements are the needs to achieve a reasonably high irrigation efficiency in order to conserve usually scarce and expensive irrigation water and avoiding the creation of a high water table.

In the processes of irrigation and drainage, soil porosity is the most important soil property. Soil pores vary in size from large to small (capillary). In natural field conditions, large pores are created by a variety of causes such as tillage, root activity or cracking. When all pores are filled with water after a rainfall or irrigation application, the soil is saturated. In this situation water in large pores drains quickly by gravity. It was thought that this water moved directly down to the water table, but recent evidence indicates that it may move through capillary pores upward (Miller and Aarstad, 1972). In any case, the rate of drainage is directly related to soil pore sizes. Coarser-grained sands drain quickly. Therefore, water for plant roots is not available for long. In finer-grained clays, the soil acts as a storage reservoir (more capillary pores). When water is drained out of all the larger pores, the soil is said to be at field capacity. This is an equilibrium state.

It can be seen that soil structure, porosity and texture are critical factors in soil
water movement and retention. Because clays furnish most of the internal surface of a soil and because of their colloidal properties, the clay fraction controls the most important soil properties (Kramer, 1969). In soils, water and dissolved substances may move as mass flow or diffusion, the driving force of which is concentration gradient, is relatively unimportant in soil water movement except in fairly dry soils. Whereas the mass flow is the motion of a column of liquid including all dissolved contents. The velocity of mass flow is proportional to the net pressure and gravitational gradients. It is at a maximum in saturated soils and decreases with the drying of soil. Water moves more slowly in drying soils. Such movement undergoes an interesting reversal with texture. Vapor transfer is also probably important in drying soils, and is largely a temperature-dependent function (Day et al., 1967).

In order to apply water most efficiently, knowledge of the optimal rate of application is useful. The most obvious factors influencing infiltration rates have been soil texture, surface aggregate structure, depth of applied water, presence and depth of impermeable layers, and soil water content at the time of irrigation.

The water table is defined as the locus of points at which the soil water is at zero pressure. Below the water table is the saturated zone, where water is at positive pressure. Water climbs above this zone into the unsaturated zone by capillary forces. The amount of water in the "capillary fringe" zone decreases with distance above the water table (Moore, 1939).

To understand water management, more importantly water table management, research information is necessary. This information is commonly acquired with lysi-
meter studies. This is the only method by which a researcher can control field data irregularities and by which the experimenter is able to determine every term in the water balance equation (Boumans, 1963). Lysimeters serve as a tool for variety of studies including salt balance studies (Bower et al., 1969). Evidently the lysimeter is flexible in concept (Bingham, et al, 1971) in studying the water, salt balance, and other solutes of environmental concern.

The design of efficient agricultural water management systems is becoming more critical as salinity problems, production costs, and farm prices increase. Optimum soil water and chemical conditions need to be studied for successful crop production and pollution control. Waterlogging as well as deficient soil water are harmful for crops. One of the parameters affecting plant growth requiring artificial drainage is the water table depth (Wesseling, 1974).

Various field and lysimeter studies (Eden, et al., 1951; Williamson and van Shilfgaarde, 1965) have been conducted to determine crop response to water table depth, but no consideration has been given to salinity effects. Some laboratory studies (Harris and van Bavel, 1957) have been carried out to examine the effects of various gaseous compositions in the root environment and the effect of waterlogging, but very little is known when oxygen is not available and the problem is further complicated with salts due to osmotic effects.

In arid regions where agriculture is dependent on irrigation, land drainage is necessary to obtain adequate leaching of salts. Water table management (WTM) has been shown to be feasible method of crop water management (Shirmohammadi et al.,
1985). Previous research has shown the applicability of available design methodology for drainage, controlled drainage, and controlled drainage - irrigation system (Shirmohammadi et al., 1991). Apart from this, the effects of water table on water quality are an important part of the research effort (Thomas et al., 1991). Past and current research has indicated the potential for reducing nitrate-nitrogen and environmental hazards to subsurface and surface waters with a controlled drainage - irrigation system (Thomas et al., 1991). The drainage system has an effect on the shallow ground water quality (Stone et al., 1989).

Other studies have evaluated individual components in WTM systems including the design of research systems, the hydraulic characteristics of control devices, and improved methods of measuring the depth to the water table (Shirmohammadi et al., 1991, Thomas et al., 1990; Smith et al., 1989; Maw and Thomas, 1988).

Minimization of the off-site impacts of agricultural production will require a better understanding of the mechanisms of transport of nitrate-nitrogen and salts. Very little information is available on the effect of water table management practices on the environmental fate of agricultural chemicals and on groundwater quality. Interest in the practice of water table management (WTM) by controlled drainage and subirrigation is growing at an accelerating rate to improve water quality and sustain higher crop productivity. Only a few studies have been reported in the literature with the specific objective of evaluating the ability of water table management practices to reduce negative impacts of water quality (Belcher, 1989; Evans et al., 1989; Kalita and Kanwar, 1990). According to these studies WTM practices have the potential to
reduce negative water quality impacts, but more research is needed in this area (Kanwar et al., 1991). Optimum WTM practices can result in lower nitrate concentrations in subsurface drainage discharge and improve water quality.

It was found that NO$_3$-N moved through the soil profile in very small amounts. There is sufficient evidence of nitrate movement into the water table (MacKenzie and Viets, 1974; Merva and Belcher, 1990; Loudon et al., 1986). According to them the rate of concentration depended on tillage methods. The depth to which chemicals move through soils is a complex phenomenon and many factors including soil pH, bulk density, moisture content, and weather factors influence the movement (Nofziger and Hornsby, 1986; Smith et al., 1988).

Very little is known, however, about the effects of salts on nitrate-nitrogen movement in the soil. Harmsen and van Schrevan (1955) stated that the mineralization and immobilization of nitrogen is usually a microbial process and is much influenced by soil conditions. On the other hand, Laura (1974), Bandyopadhyay and Bandyopadhyay (1983), Singh and Rai (1975), and Gandhi and Paliwal (1976) found that the decomposition rate of organic matter and mineralization rate of nitrogen decreased due to increase in salinity.

Nitrate-nitrogen movement greatly reduced in moderately well-drained soils because of reduction in effluent volume (Gillium et al., 1979). Kanwar et al. (1985) found more nitrate-nitrogen in no-till soils compared to tilled soil only after heavy leaching. Recent studies also have shown the presence of nitrate and pesticides in groundwater as a result of agricultural activities (Hallberg, 1986, 1989; Hallberg et al.,
1987). Also Hallberg (1986) has suggested that infiltration recharge may be the primary delivery mechanism of agriculture related contaminants in groundwater.

The laboratory experiments on soil columns were designed to provide a total mass balance for nitrate, salts and water. The results of this study may help identify the best management practices for water table management for salinity and nitrate nitrogen content.
MATERIALS AND METHODS

A water table management study was conducted in the laboratory using soil columns. Two types of soils were used for the study. One soil type was collected from the Subirrigation Project Site at Iowa State University Farm near Ankeny (nicollet loam soil). A pit of one meter square was dug to the depth of 60-cm. The soil was mixed thoroughly and brought to the laboratory where it was dried, crushed and passed through a 3.175 mm mesh sieve. Another soil type was brought from the bank of Squaw Creek near Ames (sandy loam soil). It was processed in the same way as that of Ankeny soil type.

Soil columns of two lengths were prepared using PVC pipe of 20-cm diameter. The lengths of the columns were 45 and 75-cm (Figure 1). The soil profiles were 30 and 60-cm in length. Constant water table was maintained below 30-cm and 60-cm in these columns. The zones of water table in the columns were filled with coarse sand.

A uniform concentration of 6400 ppm was maintained in the soil of both types by adding NaCl and CaCl₂ (1:1 ratio by weight). The salt concentration was maintained on the basis of the bulk densities of the soils. The concentration of NaCl+CaCl₂ (1:1 ratio by weight) in water table zone was maintained at 6400 ppm in water applied to maintain water table. However, the soil columns were saturated with fresh water before raising water table in the columns with salt solution.
A drain line was installed in each column between the soil and the surface of water table for drain effluent collection after every irrigation. An influent tube was also installed in each column 2-cm above the bottom to maintain constant water table by adjusting the float controlled reservoir.

After arranging these columns in randomized complete block design (RCBD) on a flat smooth table, the columns were saturated with fresh water from bottom upward with slowly raising water levels by 2-cm each time every two hours. When water reached the top of the soil profiles, the influent sources were clamped for 48 hours. Then the free water from the columns was first drained from the drain lines and then from the supply line. The drain effluents were analyzed for electrical conductivity (EC), calcium (Ca**), sodium (Na*), and pH to examine the draining of salts out of drains and from the water table zone. The saturation of columns from bottom was done to dissolve the salts as well as to ensure the field conditions of water table rise from underneath the root zone area. This phenomenon is common in canal seepage areas where irrigation source is river water.

Four irrigations were applied on the top of the columns after initial saturation from the bottom of the soil profile (subirrigation). Fresh water and nitrogen in the form of urea ammonium nitrate (200 mg/L N) was used for each irrigation. The interval of irrigation was maintained at 10 days, starting first irrigation after 72 hours of saturation (subirrigation) of columns as the drainable water from the columns was thoroughly removed by gravity flow.

After every irrigation, drain effluents from all columns were collected through
237
drain lines as well as from water table zone from influent tubes by clamping the supply lines connected with reservoir. All these samples were analyzed for the parameters described earlier plus nitrate-nitrogen.

At the completion of four surface irrigations of 1.2 liter each of water and 200 mg/L nitrogen (urea ammonium nitrate) dissolved in it, the columns were left to evaporation for 3 days and first soil sampling was done at three depths of 10, 20, and 30-cm, and 20, 40, and 60-cm 30 and 60-cm soil profiles, respectively. The subsequent two more soil samplings were done every 15 days. The soil sampling was done by using 1/2 inch diameter samplers. Before first soil sampling, the salt solution concentration in the water table zone was 6400 ppm in water, but after first sampling salt concentration was increased by six times (38,400 ppm) and room temperature was raised to 85°F from 70°F. All soil samples were analyzed for EC, Ca^{++}, Na^+, pH, and NO_3-N.
RESULTS AND DISCUSSION

Irrigation and drainage system management studies were conducted in the laboratory on simulated conditions of soil salinity and water table depths. The textural class of the two types of soils was nicollet clay loam and sandy loam. The effects of uniform salt concentration in the soils were investigated for salt leaching phenomenon, cation behavior, NO₃-N movement, and pH of drain effluents with respect to irrigations applied (amount of water and interval of irrigation), amount of effluents collected from drains, and changes in water table zone. These changes were measured and interpreted in the light of leachate analyses of electrical conductivity (EC) at 25°C, pH cations (Na⁺ and Ca²⁺), cationic ratio (Na⁺/Ca²⁺), and NO₃-N. The upward movement of salts and NO₃-N were measured after four irrigations applied and soil columns exposed to evaporation under 85°F temperature. The soil samples were analyzed for EC, pH, and NO₃-N and solute transport patterns examined.

Effects of simultaneous irrigation and drainage

Amount of drain effluents after each irrigation

Fresh water at the rate of 1200 cm³ was applied on the top of soil columns for each of four separate irrigations. After each irrigation, drain effluents were collected from all columns representing four treatments of S1D1 (Ankeny nicollet loam soil with
30-cm depth), S1D2 (Ankeny nicollet loam soil with 60-cm depth), S2D1 (Squaw Creek sandy loam soil with 30-cm depth), and S2D2 (Squaw Creek sandy loam soil with 60-cm depth). Figure 2 shows that there was decreasing trend in the amount of drain leachate with time as irrigations progressed.

Figure 2 further shows that soil type and depth both influenced the amount of leachate. Coarser the soil and shallower the depth more water came out of the drains. The analysis of variance on drain effluents is given in Table 1.

Table 1 indicates that there was nonsignificant difference in replications. This suggests that the replications within a treatment were alike and yielded similar leachate amounts. The treatment differences were very highly significant. The irriga-

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
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<td>4</td>
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<td>36255</td>
<td>3021</td>
<td>82.89 ****</td>
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<tr>
<td>ERR(b)</td>
<td>32</td>
<td>1166</td>
<td>37</td>
<td>-</td>
</tr>
</tbody>
</table>
tion interval (time) was also very highly significant. The leachate from one irrigation to the other very significantly differed. Also the interaction between irrigation and column depth treatment was very highly significant.

Electrical conductivity of drain effluents

The electrical conductivity (EC) is the function of total dissolved solids in soil or water and is a measure of their salinity levels. The EC is usually recorded at 25°C as a reference unit of measurement.

Figure 3 indicates the behavior of EC with respect to different irrigations for drain leachate samples collected from all four treatments. It further indicates that the EC values increased from one irrigation to the following irrigation except in S2D1 where the soil was coarser and depth was shallow, the highest EC values were recorded for S2D2 treatment where the soil was coarser and the column depth was 60-cm. Under S1D2 where the soil was clay loam the salt release from the soil columns was slow. Moreover, EC values increased abruptly on fourth irrigation. Analysis of variance on EC is given in Table 2.

Table 2 shows that there was nonsignificant difference in replications, suggesting that the replications within a treatment were alike in EC values. The treatments had very highly significant differences. The irrigation was highly significant for EC of leachate. The EC from one time of irrigation to the other significantly differed. Also the interaction between irrigation time and treatment was very highly significant.
Table 2. Analysis of variance on electrical conductivity (mmhos/cm) of drain effluents sampled after each irrigation for different water-table depths and soil types.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>0.02</td>
<td>0.01</td>
<td>0.03 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>3</td>
<td>789.48</td>
<td>263.16</td>
<td>6358.23 ****</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>6</td>
<td>0.25</td>
<td>0.04</td>
<td>-</td>
</tr>
<tr>
<td>IRRIG</td>
<td>4</td>
<td>398.13</td>
<td>99.53</td>
<td>4620.49 ****</td>
</tr>
<tr>
<td>TRT*IRRIG</td>
<td>12</td>
<td>1087.13</td>
<td>90.60</td>
<td>4205.55 ****</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>32</td>
<td>0.69</td>
<td>0.02</td>
<td>-</td>
</tr>
</tbody>
</table>

Calcium ion concentration in drain effluents

Iowa soils are calcareous in nature, and calcium is a predominant ion in the soil. The calcium ion does not pose any hazardous effect on crop growth. Calcium in chemical compounds of carbonates and bicarbonates increases soil pH as well as changes saline soils into alkaline categories. However, calcium stabilizes soil, maintains aggregate structure, controls dispersion caused by Na+, and increases flow of water in the soil and helps in leaching process of salts. Figure 4 indicates that leaching of calcium increased from one irrigation to the other until salt concentration in individual soil columns decreased. Calcium trends were similar to that of EC as described earlier because calcium was a major contributor in EC values. The analysis
of variance on Ca$^{++}$ in drain effluents is given in Table 3.

Table 3 shows that there were nonsignificant differences in replications. But treatments were significantly different from each other. Irrigation effects were very highly significant as so were treatment and irrigation interactions.

Table 3. Analysis of variance on Ca$^{++}$ ion concentration in drain effluents collected after each irrigation for different water-table depths and soil types.

<table>
<thead>
<tr>
<th>S.V</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>1254</td>
<td>627</td>
<td>0.46 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>3</td>
<td>9371552</td>
<td>3123851</td>
<td>2273.00 ****</td>
</tr>
<tr>
<td>ERR (a)</td>
<td>6</td>
<td>8247</td>
<td>1374</td>
<td>-</td>
</tr>
<tr>
<td>IRRIG</td>
<td>4</td>
<td>4321184</td>
<td>1080296</td>
<td>520.00 ****</td>
</tr>
<tr>
<td>TRT*IRRIG</td>
<td>12</td>
<td>16123230</td>
<td>1343602</td>
<td>647.00 ****</td>
</tr>
<tr>
<td>ERR (b)</td>
<td>32</td>
<td>66432</td>
<td>2076</td>
<td>-</td>
</tr>
</tbody>
</table>

Sodium ion concentration in drain effluents

Sodium plays a major role in saline and sodic soils. Sodium causes dispersion of soil particles, deteriorates soil structure, and reduces the rate of flow of water of soil due to its dispersing effect.

Figure 3 indicates that the Na$^+$ ion leached through soil profile at an increasing
rate as irrigations progressed but decreased after the amount of sodium decreased in
the soil profile. The sodium washed out from the soil quickly in sandy loam soil with
shallow depth of 30-cm. The analysis of variance on Na⁺ concentration in the drain
effluents is given in Table 4.

Table 4. Analysis of variance on Na⁺ ion concentration in drain effluents after each
irrigation for different water-table depths and soil types.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>463</td>
<td>232</td>
<td>0.11 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>3</td>
<td>20277945</td>
<td>6759315</td>
<td>3224.66 ****</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>6</td>
<td>12577</td>
<td>2096</td>
<td>-</td>
</tr>
<tr>
<td>IRRIG</td>
<td>4</td>
<td>708486</td>
<td>177122</td>
<td>56.27 ****</td>
</tr>
<tr>
<td>TRT*IRRIG</td>
<td>12</td>
<td>12776458</td>
<td>1064705</td>
<td>338.26 ****</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>32</td>
<td>100723</td>
<td>3148</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4 shows that replications were nonsignificant and treatments showed
significant differences, indicating that the replications were alike and behaved in the
same manner in each treatment. But treatments were not alike in showing significant
differences between each other. Irrigations and interaction of irrigations with
treatments were very highly significant, showing that Na⁺ movement with respect to
irrigation was different for each treatment as well as the interaction of irrigation and treatment was also significantly different for each treatment and each time interval of irrigation.

pH of drain effluents

One of the major physiological properties of the soil solutions is reaction with soil. The importance of soil reaction has long been recognized (Brady, 1974). Three conditions are possible: acidity, neutrality, and alkalinity. The presence of salts, especially calcium, magnesium, and sodium carbonates, also gives a preponderance of hydroxyl ions over hydrogen ions in the soil solution. Thus, pH changes with respect to:

Table 5. Analysis of variance on pH of drain effluents after each irrigation for different water-table depths and soil types.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>0.002</td>
<td>0.001</td>
<td>0.01 N.S.</td>
</tr>
<tr>
<td>RT</td>
<td>3</td>
<td>4.285</td>
<td>1.428</td>
<td>121.84 ****</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>6</td>
<td>0.070</td>
<td>0.012</td>
<td>-</td>
</tr>
<tr>
<td>IRRIG</td>
<td>4</td>
<td>6.006</td>
<td>1.501</td>
<td>209.50 ****</td>
</tr>
<tr>
<td>TRT*IRRIG</td>
<td>12</td>
<td>9.617</td>
<td>0.801</td>
<td>111.83 ****</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>32</td>
<td>0.229</td>
<td>0.007</td>
<td>-</td>
</tr>
</tbody>
</table>
to salt concentrations.

Figure 6 shows that the pH values decreased with added irrigation as irrigations progressed in almost all treatments except S2D1 where the soil was sandy loam and depth was shallow in which soil was almost reclaimed. This decrease might be due to the fact that salt concentrations increased with every subsequent irrigation in the other three treatments. As the concentrations of the salts (NaCl and CaCl₂) increased, the pH decreased. Analysis of variance on pH of drain effluents is given in Table 5.

The analysis of variance of pH (Table 5) shows that the replication differences were nonsignificant, indicating that the replications were alike. The treatment effects were very highly significant. Irrigation was also very highly significant. The interaction between irrigation and treatment was also very highly significant.

NO₃-N losses from drains

Nitrate-nitrogen losses were detected in the drain effluents. Schwab et al. (1980), Bottcher et al. (1981), and Schwab and Logan (1982) reported nitrate-nitrogen loss in subsurface drains. There is sufficient evidence that nitrate-nitrogen moves with water through the soil profile as a solute. MacKenzie and Viets (1974), and Merva and Belcher (1990) also reported that soluble nutrients and other chemicals applied to or contained in the soil may leach from the soil profile. Similarly, Loudon et al. (1986) found leaching of nutrients from the soil by percolating water. According to them the rate of concentration depended on soil tillage methods. The soils used for this study were thoroughly disturbed soils that represented fine tilth conditions. The depth to
which chemicals move in soils depends in a complex way upon a number of factors including soil pH, bulk density, moisture content, and soil organic-carbon, chemical, and weather factors (Nofziger and Hornsby, 1986; Smith et al., 1988). Very little is known about the effects of salts on NO₃-N transport in the soil. Harmsen and van Schrevan (1955) stated, however, that the mineralization and immobilization of nitrogen is usually a microbial process and is much influenced by soil conditions. But Laura (1974), Bandyopadhyay and Bandyopadhyay (1983), Singh and Rai (1975), and Gandhi and Paliwal (1976) found that the decomposition rate of organic matter and mineralization rate of nitrogen decreased due to increase in salinity. The results of our study are in agreement with these studies that mineralization was reduced by salts. At the same time, some NO₃-N may be removed from solution by adsorption and the formation of precipitates. The composition of leachate may also depend on the aeration status of the soil. Water flowing through a saturated profile continuously may have a different composition. Nitrate-nitrogen movement greatly reduced in moderately well-drained soils because of reduction in effluent volume (Gilliüm et al., 1979). It seems true that the NO₃-N concentration decreased with depth of profile. Bengtson (1991) reported that subsurface drainage reduced nutrient loss by substantial amount. Kanwar et al. (1985) found more nitrate-nitrogen in no-till soils compared to tilled soil suggesting that disturbed soil might allow more nitrate to leach. This result was not confirmed by our study. Nitrate-nitrogen losses were detected in the drain effluents in all treatments. However, the concentrations were very low. The analysis of variance on NO₃-N is given in Table 6.
Table 6. Analysis of variance of NO₃-N losses from drains after each irrigation for different water-table depths and soil types.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>REP</td>
<td>2</td>
<td>48.54</td>
<td>24.27</td>
<td>2.26 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>3</td>
<td>835.18</td>
<td>278.39</td>
<td>25.97 ***</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>6</td>
<td>64.33</td>
<td>10.72</td>
<td>-</td>
</tr>
<tr>
<td>IRRIG</td>
<td>3</td>
<td>631.66</td>
<td>210.55</td>
<td>38.45 ****</td>
</tr>
<tr>
<td>TRT*IRRIG</td>
<td>9</td>
<td>1244.42</td>
<td>138.27</td>
<td>25.25 ****</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>24</td>
<td>131.44</td>
<td>5.48</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6 indicates that the replications had nonsignificant differences. Treatments and irrigation, however, were very highly significant as was the interaction between treatments and irrigations.

Salt and nitrogen changes in water-table zone

Electrical conductivity of water table solution

The EC is the measure of total soluble solids in soil and/or water. Figure 8 indicates the values of EC of water in the water table zone after each irrigation.
applied. It indicates that the EC values increased from one irrigation to the following irrigation. As the time progressed, the salt concentration of water-table zone increased to about three times in 60-cm depth Ankeny soil (S1D2). The highest EC values were recorded for S1D2 and S2D2 treatments where the soil column depth was 60-cm. Under S1D2 where the soil was clay loam the salt release from the columns was slow and EC values increased abruptly on fourth irrigation. Analysis of variance of EC of water table water samples after each irrigation is given in Table 7.

Table 7 shows that there was nonsignificant difference in replications of

Table 7. Analysis of variance on electrical conductivity (mmhos/cm) of water-table water samples for different water-table depths and soil types after each irrigation.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>0.03</td>
<td>0.01</td>
<td>0.40 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>3</td>
<td>271.00</td>
<td>90.33</td>
<td>2742.01 ****</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>6</td>
<td>0.20</td>
<td>0.03</td>
<td>-</td>
</tr>
<tr>
<td>IRRIG</td>
<td>4</td>
<td>4074.38</td>
<td>1018.96</td>
<td>34577.49 ****</td>
</tr>
<tr>
<td>TRT*IRRIG</td>
<td>12</td>
<td>1483.78</td>
<td>123.65</td>
<td>4197.40 ****</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>32</td>
<td>0.94</td>
<td>0.03</td>
<td>-</td>
</tr>
</tbody>
</table>
individual treatments. It suggests that the replications within a treatment were similar in EC values. The treatments had very highly significant differences. The irrigation was highly significant toward salt buildup. The EC from one time of irrigation to the other significantly differed for increasing salt concentrations in the water table zone.

Table 8. Analysis of variance on pH of water-table water samples after each irrigation.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPS</td>
<td>2</td>
<td>0.09</td>
<td>0.05</td>
<td>3.26 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>3</td>
<td>1.45</td>
<td>0.48</td>
<td>34.02 ***</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>6</td>
<td>0.09</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>IRRIG</td>
<td>4</td>
<td>17.56</td>
<td>4.39</td>
<td>464.26 ****</td>
</tr>
<tr>
<td>TRT*IRRIG</td>
<td>12</td>
<td>3.37</td>
<td>0.28</td>
<td>29.68 ****</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>32</td>
<td>0.30</td>
<td>0.01</td>
<td>-</td>
</tr>
</tbody>
</table>

The interaction differences between irrigation and treatment were also very highly significant.

**pH of water samples in water-table zone**

One of the important characteristics of the soil solutions is its reaction. Three conditions are possible: acidity, neutrality, and alkalinity of soil or water. The
presence of salts, especially calcium, magnesium, and sodium carbonates, also gives a preponderance of hydroxyl ions over hydrogen ions in the soil solution. Thus, pH changes with respect to salt concentrations, especially chlorides of sodium. Figure 9 indicates that the pH values increased in the water table area with time as irrigations progressed in all treatments. As the concentration of the salts (NaCl and CaCl₂) increased, the pH decreased. Analysis of variance on pH of water table water samples with respect to time is given in Table 8.

The analysis of variance of pH (Table 8) shows that the replication differences were nonsignificant. The replications acted in the same way in each treatment. The treatment effects were very highly significant. Irrigation effect was also very highly significant.

Table 9. Analysis of variance on NO₃-N lost to the water table after each irrigation for different water-table depths and soil types.

<table>
<thead>
<tr>
<th>S.V.</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>REP</td>
<td>2</td>
<td>0.15</td>
<td>0.07</td>
<td>0.23 N.S.</td>
</tr>
<tr>
<td>TRT</td>
<td>3</td>
<td>1.38</td>
<td>0.46</td>
<td>1.44 N.S.</td>
</tr>
<tr>
<td>ERR(a)</td>
<td>6</td>
<td>1.91</td>
<td>0.32</td>
<td>-</td>
</tr>
<tr>
<td>IRRIG</td>
<td>3</td>
<td>0.69</td>
<td>0.23</td>
<td>0.79 N.S.</td>
</tr>
<tr>
<td>TRT*IRRIG</td>
<td>9</td>
<td>3.92</td>
<td>0.44</td>
<td>1.49 N.S.</td>
</tr>
<tr>
<td>ERR(b)</td>
<td>24</td>
<td>7.00</td>
<td>0.29</td>
<td>-</td>
</tr>
</tbody>
</table>
significant, and so was the interaction between irrigation and treatment.

**NO\textsubscript{3}-N losses to the water table**

In this study, though the soil was disturbed, the nitrate movement in to the water table zone was very low. Moreover the influence of different treatments was not clear. The analysis of variance on nitrate losses to water table is given in Table 9.

Table 9 indicates that the effects of replications, treatments, and irrigations were nonsignificant. The same result is indicated for interaction between treatments and irrigations. Because the surface of water table was so close to the drains, nitrate-nitrogen could not leach into salt solution of high density. Thus, there was no pattern for nitrate intake in the water table.

**Upward movement of salts and nitrogen**

**Electrical conductivity of soil extracts**

Figures 9, 10, 11, and 12 show the EC of soil samples taken from three equal depths of 10, 20, and 30-cm and 20, 40, and 60-cm from 30 and 60-cm long soil columns, respectively. These samples were taken three times at the interval of 15 days. Figure 9 shows EC values of soil extracts from 3 depths of 30-cm Ankeny nicoslet loam soil columns for three times. The results indicate that the EC values increased with time at almost all depths due to evaporation losses of water from the soil columns and upward movement of soil solution caused by moisture gradient.
Figure 9 further indicates that after 15 days the salt content at 20-cm depth decreased from the initial concentration and at the deepest level of 30-cm the salt concentration increased after 15 days due to rise of moisture from water table zone. The EC in the water table zone was 60 mmhos/cm that caused EC increase in upper horizons. Figure 10 shows that in Ankeny niconlet loam soil columns of 60-cm length, the EC values increased with time at all levels prominently. Similar trends were observed in both 30 and 60-cm long columns of squaw creek sandy loam soil (Figures 11 and 12). In these columns, however, the initial salt content in the columns was less than Ankeny soil, so the increase in EC was proportionally less.

pH of soil extracts

Figures 13, 14, 15, and 16 show the pH trends of soil extracts with column depths and time as described earlier. The results indicate that as the salt concentration increased with depth, the pH value decreased and also as the salt concentration increased in upper layers due to upward movement of salts, the pH decreased as compared to initial values in Ankeny soil. In 30-cm Squaw Creek soil columns (Figure 15) where initial salt concentration was less, the pH values increased with time up to 20-cm depth but reduced at the bottom. In 60-cm Squaw Creek soil columns, the pH decreased with depth as in the other three treatments. From one time to the other time of sampling the pH, however, values changed a little differently. For example, the pH of surface layer after 15 days increased from its initial value which may not be true because of the fact that salt concentration must have increased at this level
the pH of surface layer after 15 days increased from its initial value which may not be true because of the fact that salt concentration must have increased at this level rather than decreasing.

\( \text{NO}_3^- \text{-N retained in the soil at different depths} \)

Figures 17, 18, 19, and 20 show treatment-wise distribution of nitrate-nitrogen in soil profiles in all treatments with respect to sampling times and profile depths. The results indicate that there a mixed pattern of increase and decrease of nitrate-nitrogen at different depths and time. In 30-cm long soil columns of Ankeny soil, the nitrate concentration decreased with time at all depths (Figure 17) but the concentration was more at 20-cm depth. In 60-cm Ankeny soil, however, the nitrate concentration decreased with time at almost all depths but the trends became positively linear with increasing depth at second and third sampling periods (Figure 18). Whereas, in Squaw Creek soil, the 30-cm columns had decreasing trends of nitrate concentration with increase in depth as well as time of sampling (Figure 19). However, in 60-cm Squaw Creek soil columns the nitrate concentration increased with depth but decreased with time (Figure 20). From these results it can be concluded that nicollet loam soil holds more \( \text{NO}_3^- \text{-N} \) in upper layers than sandy loam soil. However, the \( \text{NO}_3^- \text{-N} \) decreased with time.
CONCLUSIONS

The results indicate that the amount of drain leachate collected after each irrigation decreased as irrigations progressed. The highest moisture retention was in 60-cm long nicollet loam soil. The EC value of the drain leachate increased after each subsequent irrigation in all treatments and so was the trend of Na⁺ and Ca²⁺ ions. However, the pH of the leachate decreased with increase in salt concentration from one irrigation to the other. The NO₃⁻N loss was very small from the drains.

In water table zone, the EC value increased after every irrigation applied but pH decreased with increase in salt concentration. The NO₃⁻N loss to the water table was very low.

The EC values increased with depth of columns in soil extracts but as the time of sampling progressed salts moved upward in the soil columns. A decreasing trend of pH with respect to soil depth was observed. The NO₃⁻N concentration in the soil decreased with time of sampling. However, in sandy loam soil nitrate-nitrogen moved significantly to the deeper layers compared to nicollet loam soil.
REFERENCES


Schwab, G.O. and T.J. Logan. 1982. Sediments and nutrients in effluent from subsurface drains. ASAE Paper No. 82-2550, ASAE, St. Joseph, MI.


Figure 1. Water table depths (a) 60-cm depth, (b) 30-cm depth.
Figure 2. Drain effluent amount with respect to each irrigation applied on top of the soil columns.
Figure 3. Electrical conductivity (EC, mmhos/cm) of drain effluents collected after each irrigation.
Figure 4. Calcium ion concentration in drain effluents collected after each irrigation.
Figure 5. Sodium ion concentration in drain effluents collected after each irrigation.
Figure 6. pH of drain effluents collected after each irrigation.
Figure 7. Electrical conductivity (EC, mmhos/cm) of soil solution in water table zone after each irrigation.
Figure 8. pH of soil solution in water table zone after each irrigation.
Figure 9. Electrical conductivity (EC, mmhos/cm) of soil extracts from three depths of 30-cm long soil columns of Ankeny nicollet loam soil.
Figure 10. Electrical conductivity (EC, mmhos/cm) of soil extracts from three depths of 60-cm long soil columns of Ankeny nicollet loam soil.
Figure 11. Electrical conductivity (EC, mmhos/cm) of soil extracts from three depths of 30-cm long soil columns of Squaw Creek sandy loam soil.
Figure 12. Electrical conductivity (EC, mmhos/cm) of soil extracts from three depths of 60-cm long soil columns of Squaw Creek sandy loam soil.
Figure 13. pH of soil extracts from three depths of 30-cm long soil columns of Ankeny nicollet loam soil.
Figure 14. pH of soil extracts from three depths of 60-cm long soil columns of Ankeny nicollet loam soil.
Figure 15. pH of soil extracts from three depths of 30-cm long soil columns of Squaw Creek sandy loam soil.
Figure 16. pH of soil extracts from three depths of 60-cm long soil columns of Squaw Creek sandy loam soil.
Figure 17. NO$_3$-N concentrations in soil at three depths of 30-cm long soil columns of Ankeny nicollet loam soil.
Soil \( \text{NO}_3 \)-N concentrations in soil at three depths of 60-cm long soil columns of Ankeny nicollet loam soil.
Figure 19. NO₃-N concentrations in soil at three depths of 30-cm long soil columns of Squaw Creek sandy loam soil.
Figure 20. NO₃-N concentrations in soil at three depths of 60-cm long soil columns of Squaw Creek sandy loam soil.
GENERAL SUMMARY AND CONCLUSIONS

Experiments were conducted in the laboratory under simulated saline and waterlogged conditions to study the transport of water, salts, and agricultural chemicals through short and large soil columns. The objectives of this research were to determine the effects of two soluble salts (NaCl and CaCl₂), applied at 1:1 ratio by weight in different concentrations, on hydraulic conductivity, transport of salts, and leaching of NO₃-N and atrazine to the groundwater. Also, the effects of two water table depths (30 and 60-cm) and two soil types (sandy loam and Nicollet loam) were evaluated on the reclamation of soils and fate of nitrate-nitrogen under simultaneous irrigation and drainage practices.

Two types of soil columns were constructed using PVC pipes of 20-cm diameter. In one set, 115-cm long and in the other set 45 and 75-cm long soil columns were used. The salt equilibria were obtained by mixing weighed amounts of salts in the weighed amounts of soil, and by repetitive saturating soil columns with desired salt concentrations. The salt concentrations of 3200, 6400, 19,200, and 38,400 ppm were used for different experiments.

Preparation of soil columns

Low-cost soil columns were constructed using a PVC pipe. The containers were tested and found to be leak-proof and suitable for use. The columns were packed with...
were packed with sandy loam soil at desired bulk densities for a series of five experiments, and sandy loam and nicollet loam for water table management experiment. These columns were subjected to tests on salt equilibrium, drainage porosity, and moisture distribution. Soil uniformity and column reproducibility tests for salt equilibrium indicated that salt distribution at all depths was almost uniform at different salt concentrations. However, to achieve salt equilibrium at any given salt concentration, the salts need to be applied with water flowing from the bottom of the column first and then with water coming from the top under gravity flow under a constant head or by mixing salts with soil at desired concentration. The drainable porosity test indicated that replications and treatments had no significant difference. This test indicated uniformity of soil packing and had almost uniform drainable porosity with respect to individual treatment. The moisture content test also indicated that there was no significant difference in replications and treatments showing that the soil packing was uniform in the columns.

It was concluded that inexpensive soil columns can be prepared with careful work and patience and the uniformity and reproducibility of columns can be achieved for laboratory solute transport studies.

**Behavior of salts in layered soil**

The electrical conductivity of leachate and the trend of sodium and calcium ions increased with time. However, cation ratio (Na\(^+\)/Ca\(^{++}\)) decreased as the salt
concentration increased in the leachate. Also leachate pH decreased with an increase in salt concentration.

It was concluded that with constant ponding of fresh water at 5-cm depth for 31 days the salts can be leached to lower layers in the soil profile and soil can be reclaimed to the depth of about 60-cm in 6,400 ppm salt treatment columns and 100-cm in 3,200 ppm salt treatment. This process would help successful growth of the majority of field crops.

**Saturated K of uniformly packed soil**

Saturated hydraulic conductivity (K) of sandy loam soil with NaCl and CaCl₂ salts (1:1 ratio by weight) decreased as the concentration of salts increased in the soil profile. The highest K was observed in salt free (control) treatment. The electrical conductivity of the leachate and the trend of sodium and calcium ions increased with time. However, the cation ratio (Na⁺/Ca⁺⁺) increased in 6,400 ppm salt concentration columns. In case of 3,200 ppm salt and salt free columns the cation ratio remained constant. The leachate pH decreased with an increase in salt concentration.

It was concluded that under a constant head of 5-cm of fresh water for 18 hours the salts can be leached to lower layers in the soil profile provided the drains are installed at the depth of 100-cm. The downward movement of salts increased the salt concentration in the leachate with respect to time. However, 6,400 ppm salt columns need more time to leach the salts for reclaiming the soil.
Saturated K of saline soil leached with saline water

Saturated hydraulic conductivity (K) of sandy loam soil increased as the concentration of salts increased in the soil profile (19,200 and 38,400 ppm) and leached with saline water of the same concentrations. However, K values decreased with time in all treatments. The electrical conductivity of the leachate increased with time and so was the trend of sodium and calcium ions. However, cation ratio (Na+/Ca++) increased in 19,200 ppm salt concentration columns but decreased for about 20 hours and then increased in 38,400 ppm salt concentration treatment.

It was concluded that under constant head of 6-cm of saline irrigation water for 36 hours the soil permeability can be increased for a saline soil.

Saturated K and transport of NO₃-N and atrazine

Saturated hydraulic conductivity (K) of sandy loam soil increased with increase in concentration of NaCl and CaCl₂ salts in the soil profile and leached with fresh water. The highest K was observed in 38,400 ppm salt concentration treatment. However, K values decreased with time in all treatments of 0, 19,200, and 38,400 ppm. The electrical conductivity of the leachate and the trend of sodium and calcium ions decreased with time due to dilution effect. The cation ratio (Na+/Ca++) was almost constant for 38,400 ppm salt concentration, however, it increased with time in the other two treatments. The pH of the leachate increased with a decrease in salt concentration. The NO₃-N concentration increased with salt concentrations and time.
at all depths of the profile but decreased with depth in all treatments. However, the highest loss of NO$_3$-N was in 38,400 ppm salt concentration soil at almost all depths. The loss of NO$_3$-N from the bottom of the columns had a similar trend as at different depths. The atrazine concentration in the leachate from column bottoms increased with increase in soil salt concentration. Also, atrazine loss increased with time in all treatments.

**Water-table management for salts and nitrate-nitrogen**

The results indicate that the amount of drain leachate collected after each irrigation at the interval of 10 days decreased as irrigations progressed. The highest moisture retention was in 60-cm long nicollet loam soil. The EC value of the drain leachate increased after each subsequent irrigation in all treatments and so was the trend of Na$^+$ and Ca$^{++}$ ions. However, the pH of the leachate decreased with increase in salt concentrations from one irrigation to the other. The NO$_3$-N loss was very small from the drains. In water-table zone, the EC values increased after every irrigation but pH decreased with increase in salt concentration. The NO$_3$-N loss to the water table was negligible. The EC values in soil extracts increased with depth of soil, but as the time of sampling progressed, salts moved upward in the soil columns. A decreasing trend of pH with respect to soil depth was observed. The NO$_3$-N concentration in the soil decreased with time of sampling. However, in sandy loam soil nitrate-nitrogen moved significantly to the deeper layers compared to nicollet loam soil.
SUGGESTIONS FOR FURTHER STUDY

This study reports the effects of two salts, (NaCl and CaCl₂), on hydraulic conductivity, transport of nitrate-nitrogen, and leaching of salts through 100-cm long disturbed sandy loam soil in layers and uniform columns under different salt concentrations ranging from zero to 38,400 ppm in 1:1 ratio of these salts by weight. Also, this study reports the effects of two water-table depths (30 and 60-cm) on the reclamation of two types of soil (sandy loam and nicollet loam) and movement of nitrate-nitrogen under simultaneous irrigation and drainage systems.

Although, the results of these experiments indicate the usefulness of the study in this area of salinity and waterlogged soils, yet more work is required for thorough knowledge of the subject. For example, the experiment on disturbed layered columns of 100-cm length gave an understanding of the salt leaching phenomenon, but we need to study undisturbed soil columns to represent field situations. Also, different soils may behave differently which may also be studied for better understanding of salts leaching with respect to soil texture and particle composition. Similarly, for disturbed soil columns with uniform density and particle composition, we need to expand research efforts to understand varying soil situations.

This study also reports that nitrate-nitrogen and atrazine movement increases with salt concentration. Again, the present study cannot generalize the results for application for all situations under different soil and field conditions. Many studies in
the area of fertilizers and pesticides have been reported in the past, but very little is known about their behavior in saline and waterlogged soils. Thus, such studies are needed to represent arid and semiarid regions’ soils with salinity problems for the fate of agricultural chemicals and water quality.

Investigations should also be continued in the area of water-table management for reclamation of salts in the presence of water table especially when the water in the water table zone is brakisk and moves upward when the fields are fallow. Under these situations, concerted and continuous research efforts are needed to solve the problems of farmers especially when there is no drainage system simultaneous to irrigation system. Therefore, compromising studies should be made for specific salts available in the soil and/or irrigation water for specific crops to be grown. Also, to increase the potential use of fertilizers and pesticides and avoid water quality problems created by man-induced agricultural chemicals, we should study each salinity and waterlogging problem separately and then coordinate them into a multidimensional study and generalize the practices of irrigation and drainage through computer modelling.

Since, salinity and waterlogging problems are of international concern, collaborative research work should be done in this area with participation of foreign schools especially Pakistan, India, and Egypt where such problems exist.
REFERENCES


Boddy, P.L., and J.L. Baker. 1990. Conservation tillage effects on nitrate and


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289-293.


U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. U.S. Salinity Laboratory Handbook 60. United States Department of Agriculture, Washington, D.C.


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