PREDICTION OF HYDRAULIC CONDUCTIVITY CHANGES USING SOIL CHARACTERISTICS

by

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ABSTRACT

Permeameter experiments were performed on six Arizona soils using a solution of 12.5 meq/l and varied sodium concentrations. Hydraulic conductivities for five soils were reduced 60 to 95 percent for input solutions having maximum sodium adsorption ratios (SAR) of 25. Effective soil sealing occurred even though the soils were alkaline.

Sealing with sodium appears nearly irreversible at low solution concentrations and saturated conditions. The soil having the highest initial hydraulic conductivity recovered less than 20 percent of the original conductivity upon reapplication of a calcium solution. These results are useful when considering sealing small ponds by sodium applications.

Hydraulic conductivity changes from increases in solution SAR were described mathematically using two empirically determined parameters that appear unique for each soil at a constant concentration. The parameters found for this study, plus those found from data of previous studies, were compared using multiple regression analysis to determine the most significant soil properties in predicting conductivity changes. Soil texture has the greatest influence on the parameters.

An equation derived by combining data from eleven alkaline soils was selected as best for predicting hydraulic conductivities resulting from SAR changes. Predictions should be improved if additional soil data were available for analysis.

CHAPTER 1

INTRODUCTION

Knowledge of the flow rate of water which a soil will transmit under ponded conditions is important to predict the amount and depth of moisture movement. An assessment of hydraulic conductivity, either by direct measurement or by comparison with similar soils, is necessary in most cases before a decision is reached on the suitability of the soil for a particular purpose.

In agriculture, soils having sufficient permeability to maintain drainage and prevent salt accumulation damaging to crops are desired. Areas recharging water to aquifers, either naturally in streams and normally dry river channels, or artificially using spreading basins or recharge pits, also need high permeability to accomplish that task.

Soils having low permeability are desirable where movement of water into the ground is undesirable. Examples include industrial and mine tailings ponds having potential heavy metal contaminants or sewage oxidation lagoons that may pollute groundwater with nitrates. In other cases, restricted movement is desired to prevent losses from ponds or lakes used as water sources for domestic, agricultural, or recreational purposes. Examples include reservoirs for drinking water, runoff captured for irrigation or stock watering, and artificial lakes created for water-based recreation or aesthetic enjoyment.

Hydraulic conductivity is markedly influenced by the quality of water applied to the soil. High sodium-low salt waters can cause deflocculation and dispersion of clays with the accompanying lowering of hydraulic conductivity. The effects of differing quality water on soil hydraulic conductivity has been documented by several researchers. This information has been used in recent years to assist in the sealing of small ponds and lakes by application of sodium salts.

Less information is available regarding prediction of the magnitude of conductivity change that can be expected with high sodium waters. This research attempts to provide a method to predict water-quality induced hydraulic conductivity changes using routinely determined soil characteristics.

Specific objectives of this study were:

1. To determine the reduction in hydraulic conductivity of several well-characterized, Southwestern soils when leached with constant concentration solutions having different sodium-calcium compositions.
2. To establish the extent that the hydraulic conductivity reductions obtained are reversible by a change in the sodium-calcium composition of the solution.
3. To quantitatively describe hydraulic conductivity changes using an equation involving characteristic parameters.
4. To compare results of hydraulic conductivity reduction from this study with results of other researchers to establish applicability of the method.

5. To relate the hydraulic conductivity changes to easily determinable soil characteristics that allow a prediction equation to be derived.

To satisfy the above goals, permeameter studies using six Arizona soils were conducted, the data combined with information available from earlier research, and the results compared by use of statistical methods. The following chapters present the specific procedures used to attain all of these objectives and discuss their accomplishment.

CHAPTER 2

LITERATURE REVIEW

The flow of a viscous liquid through a saturated porous medium is commonly expressed by Darcy's Law:

$$q = Ki \tag{1}$$

where q is the flux (discharge rate per cross-section area), i is the hydraulic gradient, and K is the hydraulic conductivity (Hillel, 1971). q is additionally described as a macroscopic flow velocity vector with dimensions length per unit time (cm/sec), which averages the overall microscopic velocities as liquid moves through the medium's total volume. The hydraulic gradient, i, is the change in hydraulic head (Δh) with sample length (L) and is dimensionless when h is expressed in units of length (i.e., cm H_2O per cm sample length for cgs system of units). Thus, the hydraulic conductivity, K, has the same units as the flux, q.

In vector form, Darcy's Law becomes:

$$\bar{q} = - K\nabla H \tag{2}$$

For a one-dimensional system, as assumed in this research, the differential form is:

$$\bar{q} = - K \frac{dH}{dx} \tag{3}$$

The negative sign indicates that flow is in a direction opposite to the increase in head.

Deviations from Darcy's Law occur when inertial forces approach resistive forces and flow ceases to be laminar. These conditions are met only in porous media with large openings (e.g., solution cavities), or in areas of steep hydraulic gradients (e.g., near wells). McNeal (1965) documents some research that found deviations at low hydraulic gradients for very fine-grained materials such as sodium saturated montmorillonite. However, the soils and methods to be described in the present research do not violate any of the above criteria and, therefore, further discussion of deviations from Darcy's Law is unnecessary here.

Hydraulic conductivity is a function of both the porous medium (intrinsic permeability) and the viscous fluid. Fluid variables are viscosity, ν, and fluid density, ρ. Use of these parameters allows comparison between such fluids as air and water or water and oil. Variations in viscosity or fluid density in solutions to be described in the current research are negligible compared to changes in the soil parameters during flow and, therefore, these effects are not considered further.

Variables Affecting Hydraulic Conductivity

The hydraulic conductivity is affected by many variables, including physical, biological, and chemical characteristics. A short discussion of hydraulic conductivity as it relates to each of these is given below.

Physical Effects

Among physical considerations are those of texture and structure. A sandy soil will commonly have a higher hydraulic conductivity than finer-grained soils. Also, a sand or silt having a wide mixture of grain sizes will generally have a lower hydraulic conductivity than a soil of one grain size because the mixed soil will have pores blocked by interstitial grains.

Compaction will reduce porosity and conductivity by breaking the natural soil structure. Fracture openings are eliminated and soil aggregates along with single grains are combined into one massive unit, greatly reducing hydraulic conductivity. The use of porosity to estimate hydraulic conductivity, as in the Kozeny-Carman equation (Hillel, 1971) leads to difficulties in soils, especially fine-grained, where pores may not be interconnected due to arrangement of packing or where cracks and fissures can add little to porosity but could provide large increases in hydraulic conductivity.

The distribution of pore sizes in the soil would be a more effective method of characterizing hydraulic conductivity if that property could be described directly. Unfortunately, this parameter must be found for each soil using soil moisture characteristic curves determined by measuring moisture content at varying suction levels. Additionally, in expansive soils, the pore-size distribution changes as the larger pores are destroyed during swelling of the partially confined matrix. The use by McNeal (1965) of a pore-size model resulted in over-estimation of hydraulic conductivity from 2 to 70 times values found by direct measurement.

Another physical effect on hydraulic conductivity is the method of wetting. Air entrapment in pores during wetting will decrease conductivity. The effect of air can be reduced by wetting from the bottom or by displacement of air by CO_2 before wetting.

Biological Effects

Biological effects include the macro effects of organics on the soil. These usually increase hydraulic conductivity and include cracks due to root penetration; and worm, insect, and decayed root holes. Organic residues from the growth process mixed with the inorganic soil fraction also produce higher hydraulic conductivities by providing for stabilization of soil aggregates and reducing bulk density. Worcester (1967) provides a review of literature relevant to preserving high conductivity by use of organic matter.

Microorganisms acting on the organic material can produce both an increase or decrease in hydraulic conductivity, depending on circumstances surrounding their action. A significant amount of literature is available describing the role of microbial action in producing stable soil aggregates that help to maintain high conductivity (Worcester, 1967). However, the action of microorganisms likewise can decrease hydraulic conductivity by clogging of soil pores with microbial cells or by-products of microbial metabolism (Allison, 1947). Also, further action by microbes on previously stable organic-cemented aggregates can reduce hydraulic conductivity, as was reported by Allison (1947) and other researchers in a review by Worcester (1967). Results of the study by Worcester (1967) on cyclic flooding during water-spreading operations showed that reduced hydraulic conductivity due to microbial e-fects were reversed when the flooded areas were allowed to dry at least 50 percent of the time in two-week, flood-dry cycles.

Chemical Effects

In addition to the physical and biological effects, the soil chemical composition plays an important role in determining the hydraulic conductivity of soils. The soil pH, cation exchange capacity (CEC), and exchangeable sodium percentage (ESP) are among some variables that indicate the type and amount of chemical components in the soil and how they might interact to produce changes in hydraulic conductivity. For example, a soil having a high CEC with high exchangeable sodium might have a low hydraulic conductivity relative to one having the same CEC but with high amounts of calcium salts. The role of CEC and ESP are reviewed further in later discussion of clay mineralogy and dispersion of clays.

In a study of the effect of pH, Martin, Richards, and Pratt (1964) found that the same quantities of sodium reduced the hydraulic conductivity more in acid than in neutral or alkaline soils. The reason for this decrease is that, at the acid pH 4 level, cation exchange capacities were found to range from only 62 to 78 percent of the original CEC values at pH 7. Therefore, the same level of sodium represents a greater percentage of the exchangeable sites and causes reduction in hydraulic conductivity.

Soil Mineralogy

More difficult to determine, but of high importance as an indicator of soil chemistry, is the mineralogical composition of the soil. It is this foundation material, acted upon by various amounts of air, water, and dissolved solutes in the water, that determines how hydraulic conductivity will be affected. The interaction of dissolved salts and solution concentrations with minerals to produce changes in hydraulic conductivity will be discussed in a following section.

Reactions between the inorganic minerals and water that affect hydraulic conductivity occur in the clay fraction of the soil. Chemically, this fraction contains mostly layered alumino-silicates of the 1:1 ratio (tetrahedral to octahedral layers), such as kaolinite, and the 2:1 structural minerals such as montmorillonite, vermiculite, and illite.

Of the 2:1 mineral group, montmorillonite (and to some extent vermiculite) clays have negative electrical charges and expanding lattices that allow cation movement into and out of the colloidal micelle. Increasing the amount of moisture in montmorillonite leads to lattice expansion and changes in volume as water molecules carrying the cations occupy space between the layers.

Measurements of cation exchange capacities for montmorillonite clays can produce high values of about 100 milliequivalents per 100 grams of soil. Illite clays, with tighter binding between layers, have fewer surface area sites available for exchange and lower CEC values. Kaolinite clays have the individual layers joined by hydrogen bonding and little expansion occurs in these clays. Because of low surface areas, CEC values are also low, ranging from 4 to 9 meq/100 g (Hillel, 1971).

Determination of type and quantities of clays present in a soil can be difficult. X-ray diffraction techniques provide, at most, qualitative estimates of the types of clay minerals present, while the quantitative methods involve extensive gravimetric and dissolution evaluations that are only accurate within ± 5% of actual values (McNeal, 1965; McNeal and Coleman, 1966). Surface area measurements on the silt and clay fraction can indicate, to some extent, the type of clay mineral (swelling or non-swelling) present. However, since cation exchange capacity is more commonly and readily measured and because surface area correlated highly with CEC (Hillel, 1971), surface area determinations are not commonly done in routine soil analyses.

The type of clay mineral has an effect on the hydraulic conductivity. The presence of large amounts of the non-expanding kaolinite tends to produce clays with high conductivity relative to montmorillonites. Assuming constant clay content between samples, a low CEC may indicate the presence of kaolinitic or illitic clay and, therefore, a high conductivity relative to the other samples. Hydraulic conductivity in montmorillonite is related not only to CEC but also to the type of cation. Conductivity can vary by factors greater than ten, depending on montmorillonite presence in a sodium or calcium saturated system (Shainberg and Caiserman, 1971). The effects of cations in the percolating solution are discussed in the next section.

Some soils retain high hydraulic conductivity even with the presence of expanding clay minerals. Research has shown that cementation action of colloidal oxides of iron and alumina produce stable aggregates that favor high soil permeability (McNeal et al., 1968).

In spite of the above exception, soils having clays with expanding structures and high surface areas are still most subject to dispersion, leading to a reduction of permeability. Due to isomorphous substitution and incomplete charge neutralization of the terminal atoms on clay lattice edges, clay particles are charged (usually negatively) and attract ions of opposite polarity. The surface of the hydrated clay particle and the swarm of neutralizing ions which have a decreasing intensity outward from the surface are together known as the diffuse double layer. When the ion is a highly hydrated, monovalent cation (e.g., sodium), it is further away from the clay micella surface than is true for a less hydrated divalent ion. The amount of a monovalent ion species present is expressed as a percentage of total exchangeable cations (CEC) such as exchangeable sodium or potassium percentage (ESP or EPP). The clay is referred to as dispersed when individual particles remain apart as a result of prominent double layers.

The exchange of divalent or trivalent cations for monovalent ions will compress the double layer as the higher charged ions have a greater affinity for the oppositely charged clay surface. A high concentration of dissolved salts will also compress the layer. Compression of the layer, by whatever method, overcomes individual micelle repulsive forces and allows short-range attractive forces (London-Van de Waals forces) to predominate and join the particles. This process, flocculation, produces the enlarged particles called flocs. Van Olphen (1963) provides a more complete description of double layer theory and the colloid chemistry processes of flocculation and dispersion.

The presence or combination of high sodium ion concentrations (e.g., high ESP) leading to dispersion, and the expanding clay minerals that swell upon hydration (e.g., montmorillonite), results in severe reductions in soil hydraulic conductivity. Several studies which have been conducted recently examine the effects of sodium on infiltration and hydraulic conductivity of soils.

Khattak (1969) examined the effect of exchangeable sodium percentage of clays on reducing infiltration in artificial soils created by mixing the clays with salt-free sand. Bentonitic, kaolinitic, and illitic clays were first calcium-saturated then combined with the sand. The resultant clay-sand mixtures were treated with sodium chloride to achieve 0, 8, 15, or 30 percent exchangeable sodium ions, and subjected to artificial rainfall from a rain simulator. Runoff was then measured for each mixture and treatment. Runoff from the bentonite mixture, initially twice as great before ESP treatment as either of the other sand-clay mixes, had an increase of 56% from original values for a treatment level of ESP 15. Runoff from the kaolinite and illite mixtures is increased by 201 and 131.5 percent of initial values at ESP 15, respectively, but never exceeded actual values for bentonite runoff at any ESP treatment level. Conclusions reached for the study were that decreased infiltration with resultant increase in runoff could be achieved with 8-15 percent ESP treatment levels without harmful soil effects. Bentonitic soils surpassed kaolinitic and illitic artificial soils in decreasing infiltration; however, the kaolinitic soils had the largest percent decrease as a result of the sodium applications.

Another study examining the influence of sodium on water movement was completed by Krapf (1969) for 13 Arizona rangeland soils. Comparisons by regression of hydraulic conductivities of untreated soils versus pH produced a correlation of r = 0.6. Hydraulic conductivities were measured again after ESP treatments of 7, 15, and 30 percent. All soils had hydraulic conductivity reductions of at least 87% for ESP 30 and, with one exception, at least 80% decreases for ESP 15. Nine of the soils had at least a 95% decrease at ESP 30. Even soils high in kaolinite relative to other clay minerals experienced large decreases at the higher treatment levels. After treatment, the resultant hydraulic conductivities at all treatment levels were combined and compared with the amount of sodium applied. They were found to be inversely related, but with a correlation coefficient of only r = -0.5.

Another point, not examined by Krapf (1969) but relevant to the current discussion, is the relationship of hydraulic conductivities for the treated soils to clay percentages. The relation of conductivity to clay reported by Krapf (1969) for untreated soils is r = -0.1, but when hydraulic conductivity versus clay content is compared at the ESP treatment levels of 7, 15, and 30 percent, the resulting correlation coefficients are r = -0.5, -0.4, and -0.2, respectively. Before treatment, ESP levels varied among soils and were dependent on prior soil history.

The effect of these different levels of sodium was probably as an important variable as percent clay in determination of untreated hydraulic conductivities. After treatment, ESP levels were at a common level for all soils for any given treatment. Since ESP was no longer a variable, clay now becomes significant at the lower ESP levels. The percent clay again becomes less of a factor in reducing hydraulic conductivities as sodium treatment levels and soil exchangeable sodium percentages are increased.

Mechanisms of Hydraulic Conductivity Reduction

Some research investigations have been recently conducted to determine the processes most important in causing reductions in hydraulic conductivity. Shainberg and Caiserman (1971) determined that decreases in conductivity within an initially Ca-saturated, thin montmorillonite membrane designed to restrict most particle movement were due to closing of conducting pores by swelling as a sodium solution was applied. Only slight decreases in hydraulic conductivity were noted until the exchangeable sodium percentage reached 15%, when steep decreases occurred up to an ESP of 40%. However, their experiments with a Ca-saturated clay paste showed a sharp decrease in hydraulic conductivity with only a slight addition of sodium (ESP range 0-15%). The concluded that the reduction at low ESP levels depends on experimental conditions and restrictions on particle movement. If particles are confined, as in the membranes, dispersion at low ESP is prevented. Therefore, unless extremely restrictive conditions are present, dispersed clay packets can move easily and block big conducting pores, reducing hydraulic conductivity sharply.

For the seven soils of different characteristics studied by McNeal (1965), he concluded that dispersion and translocation of particles after interparticle bond weakening accounted for most sealing observed. Exceptions were for the two soils highest in whole-soil montmorillonite where swelling was dominant and some reversibility of hydraulic conductivity decreases occurred after reapplication of high calcium or high concentration solutions.

The mechanisms causing hydraulic conductivity decreases were examined further in an additional paper by McNeal, Norvell, and Coleman (1966), where swelling data for the seven soils were compared with hydraulic conductivity decreases. Using van Olphen's (1963) description of decreases in hydraulic conductivity as a two-step process, the authors present a possible explanation of the sealing mechanism. Bond weakening during swelling (first step) aids particle dispersion and translocation (second step). Hydraulic conductivity decreases in soils containing large amounts of expansive minerals, or in compacted and confined soils, would, therefore, be mostly due to swelling since constraints would prevent soil particles from moving a sufficient distance to allow dispersion and translocation.

In coarse-textured soils, or those containing smaller amounts of expanding minerals, dispersion and particle translocation are more important. A proposed explanation of hydraulic conductivity decreases is a rapid sealing through lodging of silt particles or clay packets in pores rather than a gradual sealing by re-orientation of the individual clay micelles. The sudden and large decreases with only a small increase in ESP observed by Martin et al. (1964), McNeal (1965), Shainberg and Caiserman (1971), and others support this former view of particle translocation.

Further evidence of a two-step process was provided by Rowell, Payne, and Ahmad (1969), using a sandy clay loam with between five and ten percent montmorillonite. The results of their studies indicated that decreases in hydraulic conductivity will be first observed at the same solution concentration where swelling begins in the extracted clay fraction of soil. The extent of the swelling then controls conductivity until clay movement and dispersion begin.

Dispersion does not have to be complete to reduce conductivities. In studies with three Arizona soils treated with sodium dispersants to seal small ponds, Nakayama (1966) found that only part of the total soil material available for movement was being dispersed. In spite of the lack of complete dispersion, the ponds were still being effectively sealed with rates from six to ten percent of pretreatment losses.

Effect of Solution Composition and Concentration on Hydraulic Conductivity

The effect of sodium salts dissolved in percolating water in reducing hydraulic conductivity when applied to soils is well known (U. S. Salinity Laboratory Staff, 1954). The sodium adsorption ratio (SAR), long used as an indicator of the sodium hazard of a water to be utilized for irrigation is defined by the relationship:

$$SAR = Na^{+}/[(Ca^{++} + Mg^{++})/2]^{1/2} \qquad (4)$$

where concentrations of the cations are expressed in milliequivalents per liter (meq/l). Examination of the equation will show that an increase in sodium concentration will have a greater effect on raising SAR than does an equivalent decrease in either of the divalent ions. It is seen, therefore, that the amount of sodium dissolved in water is relatively more important in determining SAR than the divalent ion con-concentration.

A more subtle and often overlooked point is the effect that a decrease in total concentration has on SAR. By use of the above equation, a reduction of total concentration by four ($[Na^{+}]/4$, $[Ca^{++} + Mg^{++}]/4$) will only reduce SAR by two. Therefore, as water becomes less saline, the effect of the remaining sodium and consequent reduction in hydraulic conductivity is magnified. This effect has a practical use in reclamation work where use of high salt solutions will cause soils to remain flocculated during removal of sodium by leaching (Reeve and Tamaddoni, 1965).

Among some researchers to recognize early and report on the effect of total solution concentrations on hydraulic conductivity were Fireman and Bodman (1939) and Fireman and Magistad (1945). In the earlier study, distilled water and a saline water with a total concentration of 69 meq/l and SAR of 27 were passed through two soils. They reported that hydraulic conductivities obtained for initial application of the saline solution were very much higher than those obtained from use of the salt-free water. In their work with five western soils, Fireman and Magistad (1945) obserfed that hydraulic conductivities of the tested soils decreased when water containing 25 meq/l and sodium levels of from 50 to 96 percent (approximately SAR of 4.5 to 31.5) was replaced by a "better" quality local tap water of 280 ppm with 45% sodium salts (approximately 4.4 meq/l, SAR 1.5). They concluded that water low in salts will cause pronounced decreases in hydraulic conductivity if earlier infiltrating water had high total salt concentrations, especially if the previous dissolved salts were sodium.

Henderson (1958) measured hydraulic conductivity decreases with total salt concentration reduction in four soils at several exchangeable sodium levels, all less than SAR 20. His results show extreme decreases in hydraulic conductivity in the 0-10 meq/l range for low sodium solutions (SAR $\leq$ 10). Large decreases for higher sodium concentrations were observed also at salt concentrations greater than 10 meq/l.

Several other authors have reported finding similar reductions in hydraulic conductivity over a wide range of solution concentration and sodium levels. McNeal (1965) and McNeal and Coleman (1966) tested with solutions ranging from SAR 0 to SAR ∞ for concentrations of 3.1, 12.5, 50, 200, and 800 meq/l. They reported large conductivity decreases in five of the seven soils tested in permeameters for a range of SAR values under 25 and total solution concentrations varying downward from 50 to 3.1 meq/l.

The solutions used by Naghshineh-Pour, Kunze, and Carson (1970) in research on four Texas soils were 10.5, 54, 107, and 300 meq/l, with SAR values ranging from 0 to 38. The general trend for the two montmorillonitic soils was a rapid decrease in hydraulic conductivity with increasing SAR and decreasing solution concentrations. The most pronounced reductions occurred at solution concentrations below 54 meq/l and above SAR 10. A soil with a high free-iron oxide content was little affected by the high sodium-low salt solutions. Their results were effectively presented by use of a three-coordinate axis diagram that graphically depicted hydraulic conductivity, solution concentration, and SAR changes simultaneously.

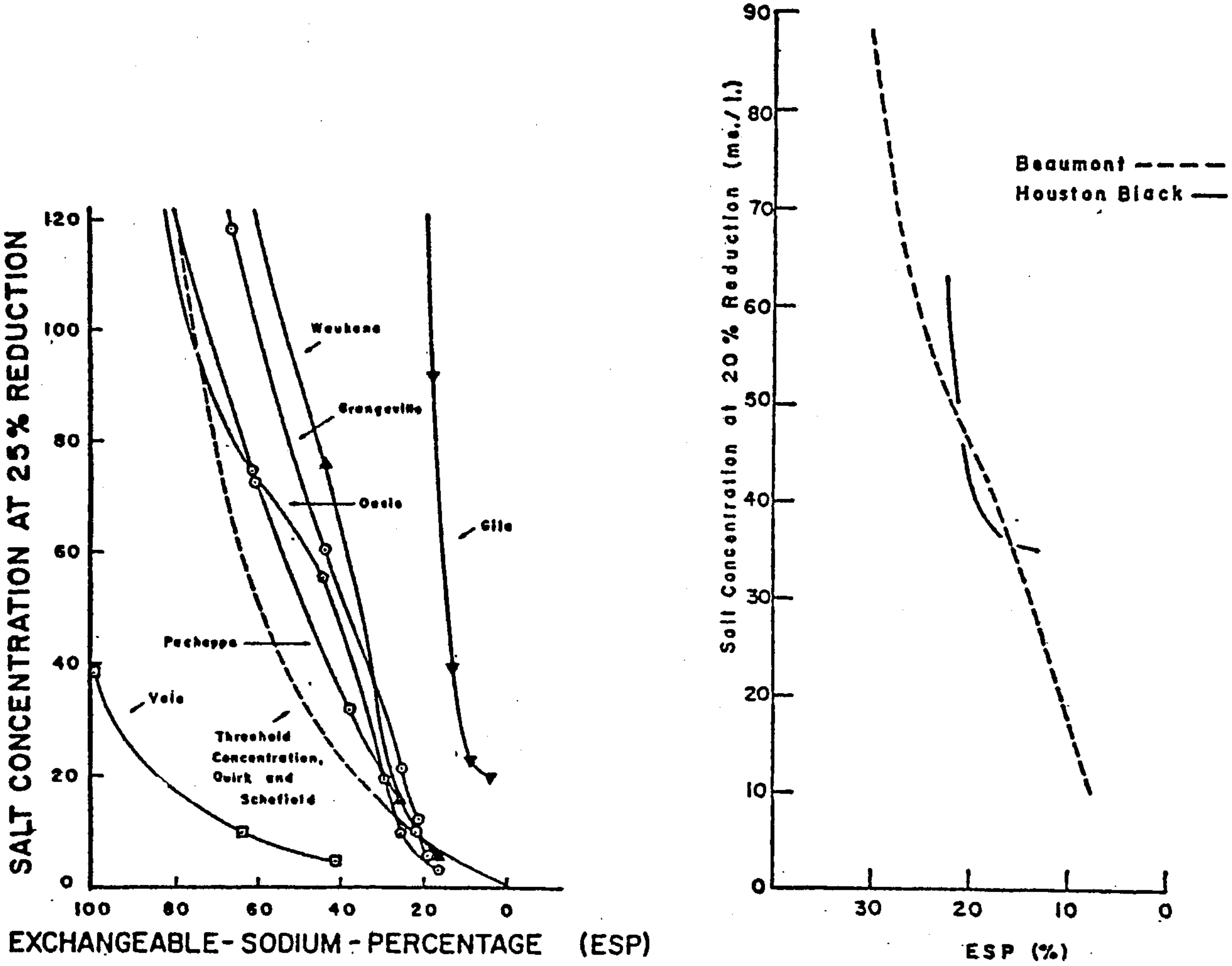
Reeve and Tamaddoni (1965) used seven high solution concentrations (63 to 4,000 meq/l) at four SAR levels (0, 80, 180, ∞) on a clay loam soil. The absolute concentration of the initial solution was found to be of much greater importance in determining initial hydraulic conductivity than was SAR. If the initial solution concentration was low, conductivity at all later concentrations was lower than if high concentrations were used initially. It is likely that, at the lower initial concentration, dispersion and blockage of pores occurred that was not reversible upon passage of the higher concentration solutions.

A concept that relates total salt concentration and exchangeable sodium percentage (ESP) to reduction in soil hydraulic conductivity is the "threshold concentration" introduced by Quirk and Schofield (1955). It is defined as the concentration of total salt and equilibrium ESP that decreases permeability 10 to 15%. For a mixed ion system of sodium and calcium salts applied to a non-calcareous, silty loam with 20% vermiculite, threshold concentration values of 5 meq/l at ESP 10, 10 meq/l at ESP 25, 25 meq/l at ESP 50, and 250 meq/l at ESP 100 were observed.

Additionally, in experiments using single ion solutions of sodium, potassium, magnesium, and calcium, they found the threhold concentration for a calcium system to be almost 500 times less than a sodium system (0.6 vs. 250 meq/l). Therefore, even in a calcium system, swelling, dispersion, and hydraulic conductivity decreases were observed for a soil at low solute concentrations.

Individual soil curves of the salt concentration at a desired conductivity reduction (usually 10 to 25%) on the vertical axis versus ESP levels on the horizontal axis have been plotted by several researchers for use as irrigation guidelines (Figure 1). Most of the curves slope upward in an exponential manner, indicating that, as ESP rises, increasingly larger amounts of salt are needed to maintain original hydraulic conductivity levels. For a particular reduction in hydraulic conductivity, as is desired in seepage control, less sodium is needed in the soil solution if the total salt concentration of the water is reduced.

Figure 1 shows very effectively the influence that soil mineralogy has on reduction of permeability. A montmorillonitic soil (Gila) measured by McNeal and Coleman (1966) for a 25% reduction in hydraulic conductivity is graphed as an almost vertical line near ESP 15 and over a wide range of concentrations. On the other hand, an amorphous soil (Vale) had only a gradual rise in slope over ESP ranges from 50 to 100%.



(a)

(b)

Figure 1. Combination of Salt Concentrations (meq/1) and ESP which Produce Reductions in Hydraulic Conductivity. -- (a) After McNeal and Coleman (1966); (b) after Naghshineh-Pour et al. (1970).

At the other extreme was a kaolinitic soil which never experienced a 25% reduction over any ESP level and could not be plotted.

Further examination of the effect of mixed-salt solutions on the hydraulic conductivity of soils was provided by McNeal et al. (1968) for the additional variables of texture, free iron-oxide content, and magnesium ion species. The result of the variation of texture in Imperial Valley soils having nearly uniform clay-fraction mineralogy, but widely varying clay contents, showed that, in addition to the expected decreases in hydraulic conductivity with increases in clay content, relative decreases occurred for mixed-salt solutions. The high sodium-low salt concentration solutions had a much larger effect in decreasing hydraulic conductivity of the soils higher in clay than on the coarser-textured soils.

Hawaiian soils of varying mineralogy, originally stable in the presence of high sodium-low salt solutions, became dispersed and less permeable when free iron-oxide contents were partially lowered by extraction. Thus, a high free iron-oxide content stabilizes soils against dispersion under high sodium-low salt conditions.

Examination of sodium-magnesium solutions which have replaced sodium-calcium leaching solutions revealed a measurable decrease in hydraulic conductivity, thus showing a difference between the ionic species. When compared at equivalent soil ESP levels, these differences were 10-15%. However, this range was within that of laboratory testing measurements for hydraulic conductivity and the authors concluded that the ions may be considered interchangeable for most purposes.

Prediction of Hydraulic Conductivity Changes from Soil and Solution Chemistry

Ample and current literature is available in soil physics regarding the physical aspects of seepage and the measurement of hydraulic conductivity necessary to predict seepage from open channels and ponded surfaces (Bouwer, 1964, 1969; Bouwer and Rice, 1969; and references therein). While acknowledging the importance of maintaining the same quality of water in tests to determine hydraulic conductivity for use in seepage prediction, Bouwer (1969) does not attempt analysis of any changes in hydraulic conductivity due to the chemical makeup of the water.

A theoretical approach to the equilibrium and movement of water in swelling soils was presented by Philip (1971) and included the introduction of an additional term, the overburden potential, to the usual components making up the total hydraulic potential (matrix, pressure, and gravity). The existence of this contributory potential should be recognized whenever addition of water results in an increase in bulk soil volume as in swelling soils. Overburden pressure, therefore, acts as an additional force in preventing moisture movement through a swelling soil.

The concept introduced by Philip (1971) was expanded by Sposito (1975) in research on seepage through thin clay soil linings used in artificial lakes. In discussing the overburden potential, he emphasizes that decreases in the seepage rate caused by swelling pressure are entirely separate from changes in hydraulic conductivity due to swelling and dispersion. After applying the overburden concept to seepage from lakes or ponds having a thin, relatively impermeable layer, he concluded that the force due to swelling pressure of clays effectively canceled the downward and relatively small gravity potential with the resulting predictive equations using only matrix and pressure potentials and coinciding with those presented by Bouwer (1969). Therefore, the change in seepage due to the effect of the overburden potential in a thin, low permeability layer is minimal.

A method for predicting hydraulic conductivity decreases by use of a "grain" soil model was presented by Lagerwerff, Nakayama, and Frere (1969). The Kozeny-Carman equation for viscous flow through unconsolidated granular material is modified through a correction for swelling and replacement of the cubic exponent of porosity with a value between zero and three (p^n, $n = 0$ to 3) dependent on the flocculation-dispersion conditions. The effect of swelling is calculated by making use of diffuse double layer theory. Information required to use this method includes solution properties (total concentration and SAR) and soil measurements (surface area, CEC, volume, and weight of soil). The method becomes tedious, however, as calculations for swelling distance must be made using incomplete elliptic integrals and an assumed value for the midplane electrical potential parameter. This parameter is allowed to vary until a fit is found between theoretical and experimental values of hydraulic conductivity. This requires a series of conductivity tests for each particular soil by varying separately both total solution concentration and SAR. Lagerwerff et al. (1969) used the theory, with some success, to predict hydraulic conductivity decreases reported in experiments by other authors. However, such prediction requires justification of the values of the porosity exponent and electrical potential chosen to fit the data.

In a review of the method, McNeal (1974, pp. 425-426) suggested that recent evidence of separation of the exchangeable cations into sodium and calcium saturated zones (domains) makes prediction difficult since the above procedure assumes uniform distribution of the ionic species. Even though the exact determination of major flow channels through the soil matrix presents an additional difficulty, he concludes the method is still a significant advance in theoretical prediction of hydraulic conductivity changes due to solution changes.

A method using mainly solution composition to predict hydraulic conductivity decreases was developed by Yaron and Thomas (1968). They utilized a mixed soil and glass bead chromatographic column to monitor ESP changes and conductivity changes with depth as a solution of constant concentration and known volume was eluted through the column. For depths up to 12 cm, the conductivity decreases were related to the mean ESP of the entire column. When plotted, data for a mean column ESP and relative hydraulic conductivity decreases approximated a linear relationship from which two empirical constants (slope and intercept) were determined for each soil and solution. Using these constants along with soil CEC, solution SAR, and volume of solution eluted, decreases in hydraulic conductivity were predicted which approached those found by experiments.

Several problems are apparent with the above approach. No attempt was made to relate the empirical constants to any soil properties; therefore, they must be measured for each soil, concentration, and SAR to be used. Also, equilibrium ESP must be experimentally determined since the authors reported values that differed greatly from the relation determined by the U. S. Salinity Laboratory Staff (1954). Use of an incorrect equilibrium ESP for this method of determining decreases in hydraulic conductivity will either over- or under-estimate the final relative hydraulic conductivity at equilibrium.

At least two authors (McNeal and Coleman, 1966; Naghshineh-Pour et al., 1970) have concluded that properties of the percolating solution alone are not enough to characterize changes in hydraulic conductivities of different soils upon exposure to given solutions. Other variables such as soil texture, ESP, and mineralogy must be brought into consideration in prediction of hydraulic conductivity changes.

Another empirical predictive approach, but one that includes the soil characteristics, has been provided by McNeal (1968). His approach was to examine the good inverse correlation between hydraulic conductivity and swelling of extracted clays (McNeal, 1965; McNeal et al., 1966). This clay-swelling model treats the mixed-ion clays as simple regional mixtures of homoionic sodium and calcium clay (domains). McNeal calculates an interlayer swelling factor (x) that is a function of the total solution salt concentration, soil ESP, an empirical interlayer spacing term (d*) dependent on solution concentration, and the weight fraction of montmorillonite in the soil (F_{mont}). With the exception of F_{mont} (which is assumed to be 0.10 unless actually known or 0.05 if none is present), x can be calculated using only soil ESP and total concentration. Using x, relative hydraulic conductivity (y) is calculated with the following formula:

$$1 - y = ax^m/(1 + ax^m) \qquad (5)$$

where m is an integer ($1 \leq m \leq 3$) dependent on soil ESP and a is empirically determined for each soil.

While x and m can be easily determined with aid of a nomogram and from parameters usually found in routine soil and water tests (i.e., soil ESP and total concentration), a must be determined by performing a permeability test starting with a high salt-high SAR solution (e.g., 800 mg/1, SAR 50 to 100) and then reducing only concentration to a relatively low level (e.g., 12.5 to 50 meq/1) and observing hydraulic conductivity decreases. This provides values of a believed to be unique for each soil at a particular soil ESP (McNeal, 1968). Further hydraulic conductivity decreases in the presence of all additional mixed-salt solutions for that soil are, therefore, predicted using Equation (5).

The procedure was tested using eleven soils of widely ranging clay content with good correlation except for very low clay percentage soils (< 6%) having ESP < 25%. The technique does seem to be useful for determining relative hydraulic conductivity values in a wide range of solutions without the need for surface area, pore-size distribution data, or precise mineralogical information. The main drawbacks of this method are the need for a series of soil permeability tests to determine the empirical constant, a, and (to a lesser extent) some minimal knowledge of soil mineralogy to estimate an initial value for F_{mont}.

Relation of Commonly Determined Soil and Solution Variables to Hydraulic Conductivity

With the state of current techniques and knowledge, exact relation of the soil descriptive variables to absolute hydraulic conductivity and changes in conductivity is extremely difficult. In addition, determination of the parameters in many of the methods described above requires extensive laboratory analysis and use of sophisticated equipment.

Easier to measure, although hard to relate explicitly to absolute hydraulic conductivity and conductivity changes induced by a percolating solution, are the soil properties of texture, cation exchange capacity (CEC), pH, calcium carbonate, and soil organic material. Two other commonly used variables indicate current condition of the soil. Electrical conductivity (EC), usually determined from the soil saturation extract, is an index of the concentration of soluble ions and salinity of a sample and, together with ESP, may indicate the extent of flocculation of dispersion of the original unleached soil. Determination of all of the above parameters is commonly done using procedures first collected in Handbook #60 (U. S. Salinity Laboratory Staff, 1954) and still in extensive use.

In natural systems, many different species of chemical ions may be found. The influence that different proportions of monovalent to divalent cations and the effect of total concentration of salts in solution have on hydraulic conductivity were discussed earlier. The former effect may be described by the sodium adsorption ratio (SAR), while the total solution concentration may be estimated from leachate electrical conductivity measurements or analyzed directly. These procedures are also described by Handbook #60 (U. S. Salinity Laboratory Staff, 1954).

The intention of this research is to attempt prediction of hydraulic conductivity decreases using soil and solution characteristics readily attainable with only a minimum of inexpensive laboratory determinations and without use of extremely sophisticated equipment and techniques. Toward that end, the more easily determinable soil and solution variables described above were utilized along with soil hydraulic conductivity experiments to describe a possible model for prediction of hydraulic conductivity decreases when percolated with solutions of known composition.

CHAPTER 3

THEORY

If a soil is leached by water of constant chemical composition with an unchanging hydraulic head gradient until the volumetric flow rate (flux) becomes constant, it may be postulated that the hydraulic conductivity (K) of a saturated soil is a function of the innate soil properties, past soil conditions, and solute concentration and composition of the percolating solution.

Among some properties that may be considered during the current discussion as intrinsic to a soil are texture (relative amounts of sand, silt, and clay), cation exchange capacity (CEC), pH, surface area, calcium carbonate ($CaCO_3$), and organic material (OM). In functional form, these may be expressed as:

$$K = f(\text{texture, CEC, pH, surface area, } CaCO_3\text{, OM, } \ldots) \qquad (6)$$

These properties may not be independent of one another as can be shown, for example, by the strong dependence of CEC on surface area, which itself is partially a property of the soil clay content. Likewise, pH is partially dependent on the amount of calcium carbonate and organic matter present. Because it exhibits a strong relationship to other variables and is also hard to measure, surface area was removed as an independent variable. Similarly, since CEC and clay are related, clay was removed from the texture term. In the discussion that follows, independence of the remaining variables is assumed. In treating these soil properties as independent variables, the actual extent of their relationships with each other should be remembered.

Soil sample conditions before packing and subsequent leaching have been shown to have an important effect on values of hydraulic conductivity. Sodium and the amount of soluble salts present before leaching can cause rapid and permanent structural changes that affect steady-state conductivity values. These changes in hydraulic conductivity are separate from conductivity adjustments caused entirely by characteristics of the percolating solution. The amount of soil exchangeable sodium may be characterized by use of the exchangeable sodium percentage (ESP), while soluble salts can be estimated using the electrical conductivity of the saturation extract (EC_e).

The relationship of hydraulic conductivity to the variables of the total solute concentration (C_T) of the percolating liquid and solution composition as characterized by the sodium adsorption ratio (SAR) were presented in the literature review of the previous chapter.

After the inclusion of soil history and solution properties, and with the removal of the dependent variables, the relationships in Equation (6) may now be expressed as:

$$K = f(\text{sand, CEC, pH, } CaCO_3\text{, OM, } \ldots\text{, ESP, } EC_e\text{, } C_T\text{, SAR}) \tag{7}$$

Other combinations may be substituted (e.g., clay for CEC) as long as the independence of the variables in the equation is maintained. A total differential, dK, may be written to examine the changes in K due to each assumed independent variable and to define a functional relationship for each such that:

$$dK = \left(\frac{\partial K}{\partial \text{Sand}} \right) d\text{Sand} + \left(\frac{\partial K}{\partial \text{CEC}} \right) d\text{CEC} + \ldots + \left(\frac{\partial K}{\partial \text{SAR}} \right) d\text{SAR} \tag{8}$$

where, for each variable examined, other variables are kept constant for that examination. If solutions of constant total concentration, but with varying SAR, are percolated through a soil with the unvarying intrinsic properties described above until a steady-state conductivity is reached, the equation may be written:

$$dK = \left(\frac{\partial K}{\partial \text{SAR}} \right) d\text{SAR} = f'(\text{SAR}) \tag{9}$$

Integrating:

$$K = f(\text{SAR}) + C \tag{10}$$

with the constant, C, containing the unexamined soil and solution variables remaining in Equation (7).

Experiments on seven soils using a variety of solution concentrations and SAR values (McNeal, 1965) show sigmoid-shaped families of curves with soil hydraulic conductivity increasing as total solution concentration increases at a given SAR. An example of these curves is shown in Figure 2 for the Waukena soil. The curves may be replotted for soils leached at one total solute concentration to show decreases in hydraulic conductivity with SAR increases. Figure 3 illustrates the variation of hydraulic conductivity with SAR at one solution concentration for three of the soils examined by McNeal (1965).

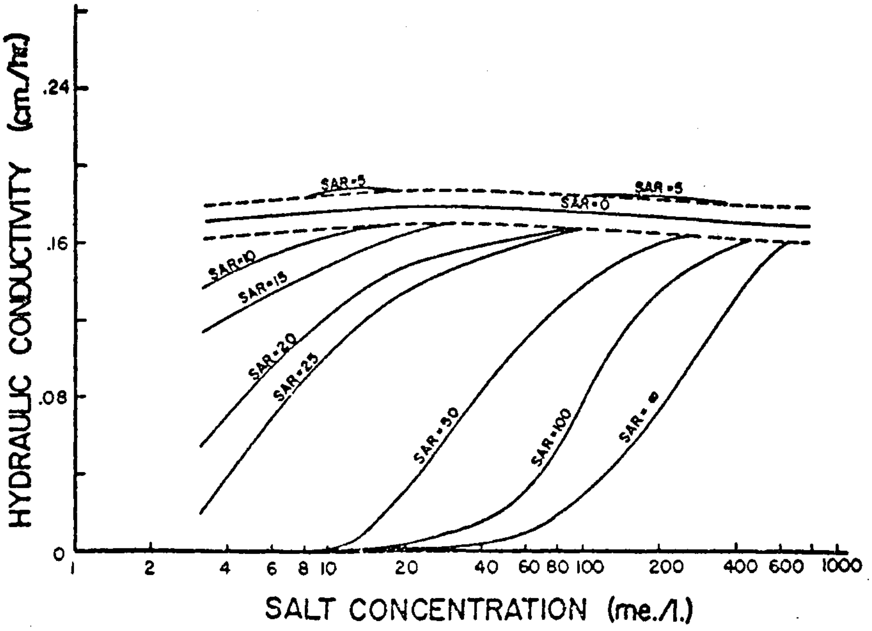


Figure 2. Families of Curves Produced when Hydraulic Conductivity Is Plotted; Salt Concentration for Waukena Clay Loam. -- No detail is shown within 5 percent of the line for SAR = 0. After McNeal (1965, p. 62).

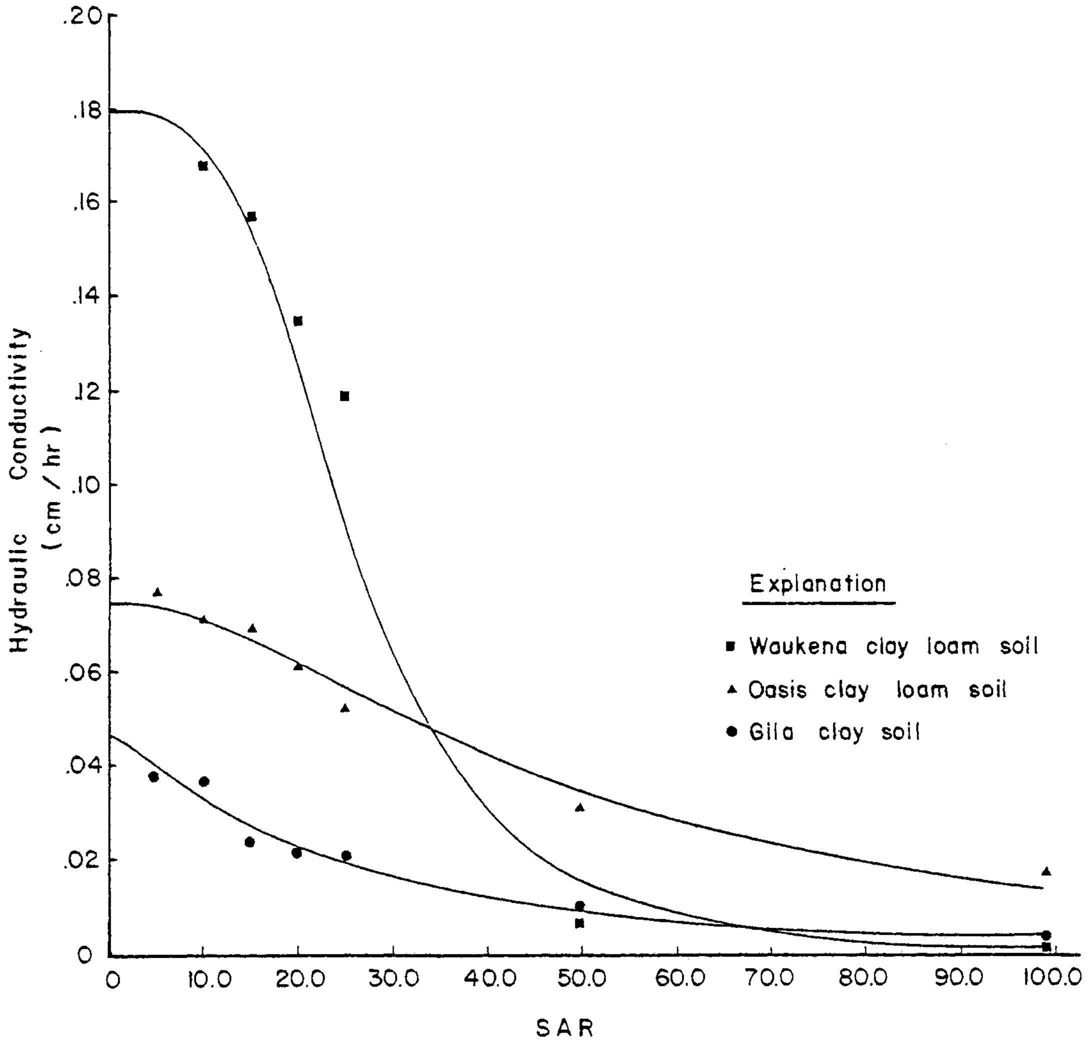


Figure 3. Hydraulic Conductivity Changes with Increasing SAR for Three Soils Examined by McNeal (1965). -- Total concentration of the solution is 12.5 meq/l. The smooth curves were produced by use of Equation (11).

When leached with a calcium solution (SAR = 0), the soils will reach equilibrated values of hydraulic conductivity, K_0. The degree of change in hydraulic conductivity when leached with a sodium solution of equivalent concentration is dependent not only on the amount of sodium, but also on the value of K_0 (Figure 3). This value of K_0, constant for any soil, is determined by the soil variables plus past soil conditions before packing and subsequent leaching. When placed in permeameters for experimental study, a value of K_0 determined for a soil also reflects the method of packing used by the investigator since original soils structure has been altered in the packing process.

A possible empirical solution for Equation (10) is given by the generalized mathematical formula for the shape of curve shown in Figure 3:

$$K = K_0 \; [1 + c(\text{SAR})^n]^{-1} \tag{11}$$

with c and n being constants. The mathematical form of this equation is similar to that used by McNeal (1968) in his clay-swelling model described previously.

To facilitate comparison among soils, a relative value of hydraulic conductivity at any SAR may be defined as follows:

$$K_R = \frac{K}{K_0} = [1 + c(\text{SAR})^n]^{-1} \tag{12}$$

To determine c and n values, Equation (12) may be modified to the following form:

$$\left(\frac{1}{K_R} - 1 \right) = c(\text{SAR})^n \tag{13}$$

By taking logarithms, the equation is linearized to:

$$\log \left(\frac{1}{K_R} - 1 \right) = \log c + n \log (\mathrm{SAR}) \qquad (14)$$

for which the constants c and n may be determined for a single soil by simple linear regression analysis from the available SAR versus hydraulic conductivity data.

It is postulated here that if solution concentration is kept constant c and n may be functions of the properties expressed in Equation (7). If sufficient information on these properties for several soils is available for examination, a predictor model using these characteristics may be developed from multiple linear regression analysis of c and n with soil data. An example of such a model for the constant n might be:

$$\begin{aligned} n = a &+ b_1[f(W_1)] + b_2[f(W_2)] + b_3[f(W_3)] \\ &+ \ldots + b_m[f(W_m)] \qquad (15) \end{aligned}$$

where $f(W_i)$ is called a predictor variable and represents any simple transformation (e.g., power, root, log, etc.) of soil property W_i, e.g., $(\mathrm{CEC})^2$, log (ESP), etc. The values b_1, b_2, ..., b_m represent coefficients of the predictor variables. The form and total number of predictor variables to be included in the model may be determined using standard statistical techniques.

Hopefully, the model can be extended to other soils if data on their soil properties are available. Values of c and n found by use of this predictor model for any additional soils may be compared to values of c and n found by performing conductivity experiments on the new soils. If necessary, the model can then be modified to reflect this increased information.

By repeating the K versus SAR analysis at different levels of solution concentration for both the current soils and any additional samples, the soil properties having the greatest effect on hydraulic conductivity at these different concentrations can be determined. With sufficient soil and experimental data to provide confidence in the determined values of c and n, it should be possible to predict changes in hydraulic conductivity with increasing SAR over a wide range of solution concentrations for soils of widely different characteristics.

CHAPTER 4

RESEARCH METHODS AND MATERIALS

The establishment of a predictor model based on readily determinable soil properties was dependent on the availability of data from studies of the effects of salt concentration and SAR on hydraulic conductivity. The published data of two studies were sufficient to begin an attempt at finding a model to predict hydraulic conductivity changes. Data on soil properties and the experimental work described below for Arizona soils provided additional information.

Physical and Chemical Analyses

Complete analyses of the seven soils of varying characteristics utilized by McNeal (1965) for the study of solution composition effects on hydraulic conductivity were available to provide data for hypothesizing a model. Similar, but less complete information was available from work conducted on four Texas soils (Naghshineh-Pour, 1968; Naghshineh-Pour et al., 1970). Tables 1 and 2 list the soil properties for both studies, including some mineralogical information. Bulk density and electrical conductivity measurements were not available for the Texas soils.

Six Southern Arizona soils ranging in texture from loamy sand to clay were chosen for testing. The characteristics of these soils are provided in Tables 3 and 4. The soils were supplied from existing

Table 1. Characteristics of Soils Used by McNeal (1965) and Naghshineh-Pour (1968) in Hydraulic Conductivity Studies.

		Characteristics[a]										
		Particle Size Distribution (%)										
Soil	Depth (cm) or Profile	(>50μ)	(50-2μ)	(<2μ)	Sample Texture[b]	pH	CEC (meq/100 g)	ESP (%)	EC_e (mmho/cm)	$CaCO_3$ (%)	Organic Matter (%)	Packed Bulk Density (g/cm^3)
McNeal												
Aiken clay loam	5-30	18.1	36.4	45.5	clay	5.7	16.2	1	0.1	0.0	3.29	1.27
Gila clay	5-20	11.9	27.7	60.4	clay	8.0	41.2	5	1.9	3.8	1.89	1.01
Grangeville sandy loam	30-60	63.2	22.7	14.2	sandy loam	7.7	16.8	1	0.7	1.5	0.30	1.32
Oasis clay loam	5-15	9.2	68.3	22.5	silt loam	7.7	14.8	54	86.3	22.7	1.99	1.41
Pachappa sandy loam	0-15	42.3	45.1	12.6	loam	7.6	10.3	2	0.6	0.1	0.92	1.37
Vale silt loam	5-15	14.3	74.4	11.3	silt loam	10.0	40.6	92	42.8	1.1	0.46	1.16
Waukena clay loam	12-50	34.7	35.2	30.1	clay loam	8.7	24.8	79	16.0	1.4	0.46	1.23
Naghshineh-Pour												
Beaumont clay	A_1	7.2	37.9	54.9	clay	5.1	41.5	1.7	--	0.0	3.10	--
Houston black clay	A_1	4.4	40.1	55.5	silty clay	7.7	58.2	0.3	--	32.8	3.30	--
Katy fine sandy loam	B_2	39.0	24.7	36.4	clay loam	5.8	16.7	10.8	--	0.0	0.50	--
Nacogdoches fine sandy loam	B_2	28.8	28.0	43.2	clay	5.4	13.8	<0.1	--	0.0	0.60	--

[a] Abbreviated characteristics: pH, pH of saturated soil paste; CEC, cation exchange capacity; ESP, exchangeable sodium percentage; EC_e, electrical conductivity of the saturation extract at 25°C; $CaCO_3$, calcium carbonate.

[b] Classification using USDA textural triangle.

Table 2. Mineralogical Composition of Soil Clay Fraction (< 2 μ) Used by McNeal (1965) and Naghshineh-Pour (1968) in Hydraulic Conductivity Studies.

Soil	Relative Amount[a]						
	Mica	Quartz + Feldspar	Kaolinite	Montmorillonite	Vermiculite	Chlorite	Other[b]
McNeal							
Aiken clay loam	1	1	5	1	1	2	2
Gila clay	3	2	2	4	2	2	0
Grangeville sandy loam	3	1	2	3	3	2	0
Oasis clay loam	3	2	1	3	2	2	1
Pachappa sandy loam	3	2	2	3	2	2	2
Vale silt loam	2	2	0	3	2	2	3
Waukena clay loam	3	2	2	4	2	2	0

Soil	Illite	Quartz	Kaolinite	Montmorillonite	Tabular Halloysite
Naghshineh-Pour					
Beaumont clay	1-2	1-2	1-2	4	0
Houston black clay	0	1-2	1-2	4	0
Katy fine sandy loam	1-2	2-3	2-3	0	4
Nacogdoches sandy loam	1-2	2-3	2-3	0	4

[a] Relative amounts assigned using system of U. S. Soil Conservation Service (1974): 0 = not detected; 1 = trace; 2 = small; 3 = moderate; 4 = abundant; 5 = dominant. Approximate percentage ranges are: trace, 5%; small, 5-20%; moderate, 20-40%; abundant 40-60%; dominant, >60%.

[b] Includes SiO_2, allophane.

Table 3. Characteristics of Soils Used in the Present Study.

		Characteristics[a]										
		Particle Size Distribution (%)										
Soil	Profile	Sand (>50μ)	Silt (50-2μ)	Clay (<2μ)	Sample Texture[b]	pH	CEC (meq/100 g)	ESP (%)	EC_e (mmho/cm)	$CaCO_3$ (%)	Estimated[c] Organic Matter (%)	Packed Bulk Density (g/cm^3)
Anthony sandy loam	A_p	69	18	13	sandy loam	8.0	5.8	7.6	0.43	0.48	0.5	1.87
Grabe loam	A_p	45	41	14	loam	7.8	15.7	13.1	5.42	6.55	1.4	1.59
Mohave clay loam	A_p	77	13	10	sandy loam	7.8	9.1	1.3	0.46	0.73	0.5	1.87
Pima clay loam	A_p	25	46	29	clay loam	7.8	22.7	10.3	3.04	6.00	1.2	1.54
Vinton loamy sand	A_p	77	17	6	loamy sand	7.9	9.2	6.5	1.11	1.85	0.5	1.70
Whitehouse	B_2	43	18	39	clay loam	7.3	22.7	3.0	0.84	2.45	0.5	1.71

[a] Abbreviated characteristics: pH, pH of saturated soil paste; CEC, cation exchange capacity; ESP, eschangeable sodium percentage; EC_e, electrical conductivity of the saturation extract at 25°C; $CaCO_3$, calcium carbonate

[b] Classification using USDA textural triangle.

[c] Estimate from Post (1975).

Table 4. Estimated Mineralogical Composition of Soil Clay Fraction (< 2 μ) Used in the Present Study.

		Soil Conservation Service[a]			Hendricks[b]
Soil	Profile	Mica	Montmorillonite	Kaolinite	Montmorillonite
Anthony sandy loam	A_p	4	2	2	Small
Grabe loam	A_p	3	4	2	Abundant
Mohave sandy loam	A_p	3	1	1	Trace (abundant at 1 meter depth)
Pima clay loam[c]	A_p	3	5	2	Abundant
Vinton loamy sand[d]	A_p	3	3	-	Moderate
Whitehouse clay	B_2	3	3	2	Moderate

[a] From U. S. Soil Conservation Service (1974): 1 = trace; 2 = small; 3 = moderate; 4 = abundant; 5 = dominant. Approximate percentage ranges are: trace, <5%; small, 5-20%; moderate, 20-40%; abundant, 40-60%; dominant, >60%.

[b] Estimate from Hendricks (1977).

[c] Soil is similar in properties and description to Pima clay loam (Gelderman, 1972, p. 62; U. S. Soil Conservation Service, 1974, p. 223).

[d] Soil is similar in properties and description to Vinton loamy sand (Gelderman, 1972, p. 62; U. S. Soil Conservation Service, 1974, p. 223).

samples assembled by members of the Department of Soils, Water and Engineering, University of Arizona. All soils were from the Ap horizon of irrigated areas of southern Arizona except Whitehouse which was obtained from the B2 horizon of a rangeland region north of Tucson. Analysis of all sample properties except organic matter and mineralogy was performed by the University of Arizona Soil and Water Testing Laboratory. Analyses were performed using criteria established by the U. S. Salinity Laboratory Staff (1954). Estimates of organic material were provided by Post (1975). Sources of the estimates of mineralogical composition are included in Table 4.

Bulk densities for soils used by McNeal (1965) were not reported. They were calculated using porosity values derived from water retention measurements of the soils and reported as part of that study. The water-filled porosity determined by the above method represents only pore spaces available for moisture movement and therefore differs slightly from the usual measurements obtained using dried material. The method of air-dry packing utilized here attempted to provide a complete breakdown of soil clods into individual particles, resulting in a higher bulk density than found for the McNeal (1965) soils. Bulk densities were not available for the soils of Naghshineh-Pour (1968).

Preparation of Soil Permeameters

Determinations of soil hydraulic conductivity was made using permeameters constructed from three-inch sections of approximately one inch I.D. plastic opaque PVC pipe. Construction details are shown in Figure 4. Fiberglass matting was used as packing material at both

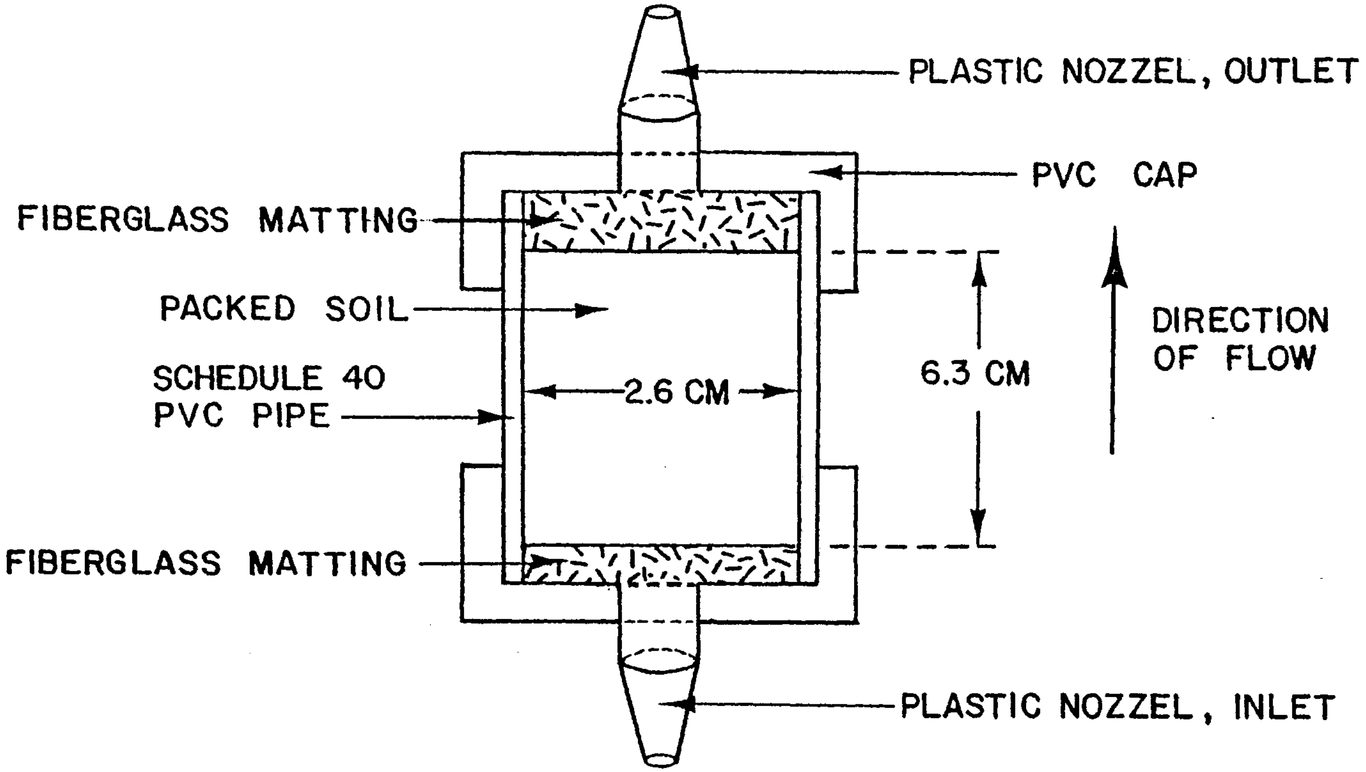


Figure 4. Details of Permeameter Construction.

influent and effluent ends. Several samples of fiberglass were mixed with distilled-deionized water and analyzed prior to permeameter construction for possible concentrations of cations that could influence hydraulic conductivity results.

An individual permeameter was constructed for each soil at every SAR. For the six soils at nine separate SAR's, 54 permeameters were prepared. This method was utilized because examination of hydraulic conductivity changes using previously unwetted samples was desired.

The selected, air-dried soil was passed through a 2-mm sieve. Soil clods were eliminated by use of a mortar and pestle. A packing procedure was used that attempted to minimize channeling effects along the outer walls. About 20 cm^3 was initially put into the preweighed column and packed using a glass rod about 5 mm in diameter. Packing continued until 70-80 percent remained intact when the column was inverted. This first packing represented 15-20 percent of the column final length. The process was repeated until the entire column was packed. A scribe was used to remove excess material at the predetermined soil depth for a final packed volume of 33.3 cm^3. After weighing and calculating the soil weight, fiberglass matting was inserted and the column capped to await saturation by the percolating solution.

Preparation of Solutions

The study examined hydraulic conductivity decreases for a total solution concentration of 12.5 meq/l. This concentration was selected to allow comparison of the results with McNeal (1965) and Naghshineh-Pour (1968). When converted to mg/l, this concentration range

(690-730 mg/l) is within that reported by Dutt and McCreary (1970) for many Arizona ground waters. Solutions of nine different SAR's were prepared using distilled, deionized water. Values selected were SAR 0, 5, 10, 20, 35, 60, 65, 100, and infinity (∞). Table 5 gives the calcium, sodium, and SAR composition of solutions used in this study. The anion used in all cases was chloride. This range of SAR values was similar to ones used in the previous studies. The water was degassed by boiling to eliminate dissolved CO_2 that might impede accurate measurements of hydraulic conductivity.

Since samples were only air-dried and not sterilized, it was anticipated that microorganism growth would occur. The soils were expected to equilibrate before changes in K due to growth became important. However, the length of time many soils required to reach a relatively constant flow rate (in excess of 25 days for numerous trials, especially at higher SAR values) provided ample time for microorganism growth. Later permeameter measurements were, therefore, made using solutions with 40 mg/l of $HgCl_2$ added to inhibit bacteria and fungal growth. The amount of calcium in solution was lowered to compensate for the addition of 0.295 meq/l of the mercury ion (Table 5), using the assumption that divalent mercury [Hg(II)] would act similar to Ca and Mg on the clay exchange complex. However, recent research (Newton, Ellis, and Paulsen, 1976) has proved this assumption incorrect, making necessary the use of corrected SAR values as shown in Table 5.

Table 5. Composition of Solutions Used in Permeameters (Total Concentration = 12.5 meq/l).

	Sodium-Calcium Solution		Sodium-Calcium-Mercury Solution		
Sodium (meq/l)	Calcium (meq/l)	Solution SAR	Calcium (meq/l)	Solution SAR	Mercury[a] at 40 mg/l (meq/l)
0.000	12.500	0	12.205	0	0.295
7.725	4.775	5	4.480	5.2	0.295
10.355	2.145	10	1.850	10.8	0.295
11.805	0.695	20	0.400	26.4	0.295
12.253	0.247	35	--	∞	0.247
12.375	0.125	50	--	∞	0.125
12.426	0.073	65			
12.465	0.035	100			
12.500	0.000	∞			

[a] Mercuric chloride ($HgCl_2$) used only with Anthony, Grabe, and Vinton soils; SAR's 0, 5, 10, 20, 35, and 50.

Hydraulic Conductivity Measurements

A diagram of the complete system used in the determination of K is shown in Figure 5. Hydraulic conductivity is found using:

$$K = \frac{VL}{At\Delta H} \tag{16}$$

where V is the volume of discharge collected during time t, L is the length of packed column, A is the cross-sectional area of column, and ΔH is the hydraulic head difference. Dimensions of V, L, A, and H are l^3, l, l^2, and l, respectively, with l (length) in centimeters. t (time) is in hours.

A constant head (ΔH) of 90.1 cm was maintained, as shown in the figure. Because the method of packing produced a high bulk density, this amount of hydraulic potential was necessary to insure completion of measurements in a reasonable time. The length of the packed column (6.3 cm) and cross-sectional area (5.3 cm^2), restrained by the capped ends and pipe interior, were assumed to remain constant for each test. The solution flow was directed upward through the soil column to minimize entrapment of air in the soil pores as the sample was saturated. Time required to saturate the sample was recorded and included the interval required to remove entrapped air.

Measurement of permeameter effluent volume was made using graduated cylinders partially sealed at the top to minimize evaporation loss between readings. Frequent readings were taken during the early hours of the test when rapid changes in hydraulic conductivity rates were occurring. When change in hydraulic conductivity became less rapid, measurements were recorded once daily.

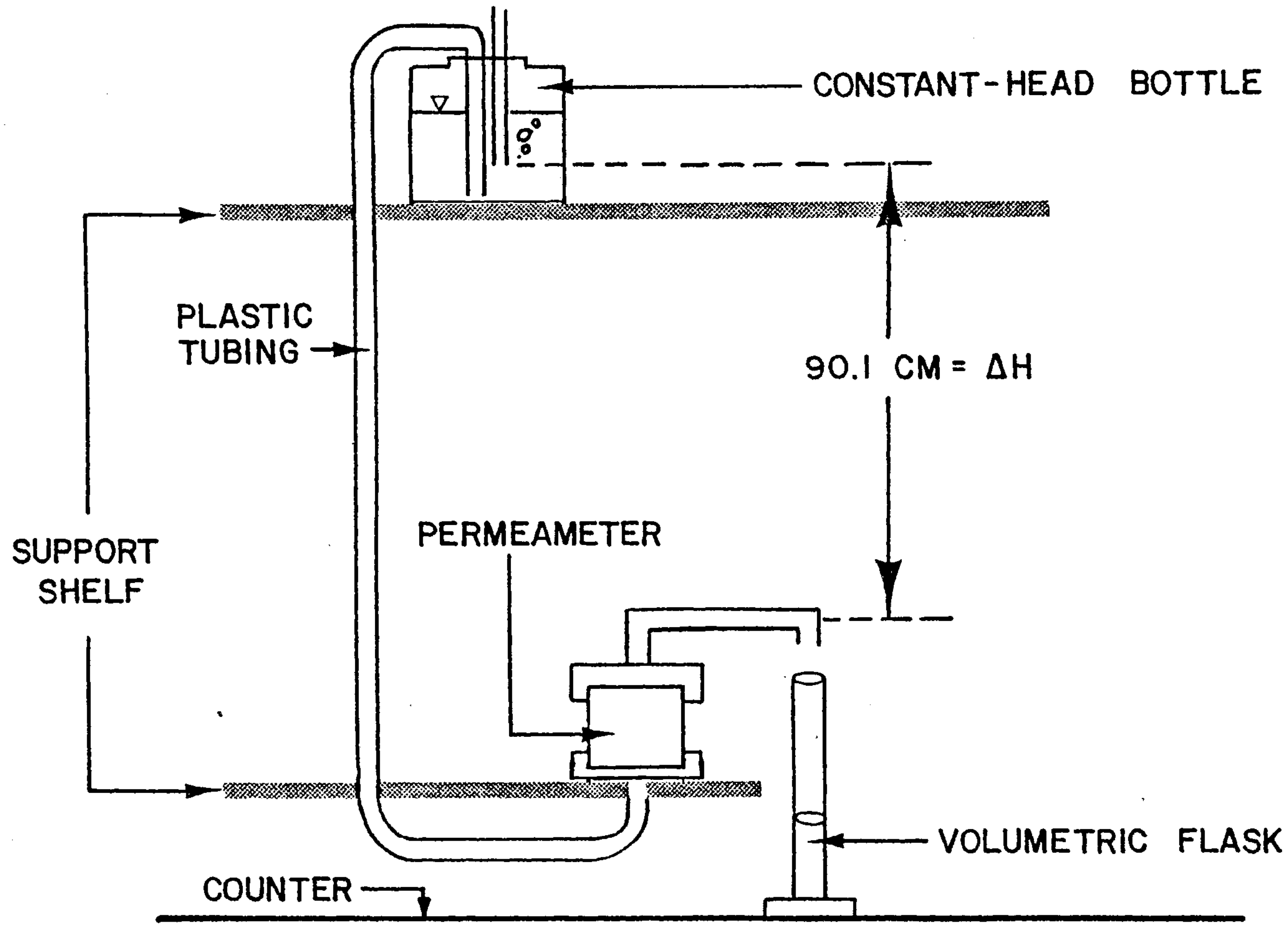


Figure 5. Diagram of Permeameter Arrangement for Hydraulic Conductivity Determinations.

Figure 6 provides an overview of the experimental equipment and shows the interconnections to soils tested with the same SAR. The shelf arrangement allowed for 36 samples to be run simultaneously. The remaining 18 soil samples plus several replicates were tested upon completion of the initial runs.

Samples of the output collected in the graduated cylinders were retained for analysis of pH, electrical conductivity, and sodium and calcium. Standard procedures, as described by the U. S. Salinity Laboratory Staff (1954), were utilized with the exception of atomic absorption for analysis of calcium instead of precipitation methods. The outcome of these analyses provide an indication of equilibrium conditions between the soil samples and the percolating solution.

Upon completion of hydraulic conductivity determinations, an experiment was performed to examine the reversibility of the conductivity decreases. Solutions of varying SAR, but constant total concentrations (C_T = 12.5 meq/1), were applied or reapplied to the packed columns. Only the Vinton soil was tested for reversibility. Similar tests on the other soils were prevented by either extreme low hydraulic conductivities with correspondingly long times to equilibrate, or by growth of microorganisms.

Figure 6. Arrangement of Solutions and Permeameters for Hydraulic Conductivity Determinations.

CHAPTER 5

RESULTS AND DISCUSSION

The results of the permeameter experiments are presented and discussed in this chapter. Also included are an examination of the reversibility of sealing for one of the soils studied, selection of a representative hydraulic conductivity for each solution SAR, and determination of the empirical parameters used to characterize changes in hydraulic conductivity corresponding to changes in SAR. The parameters are compared with those of other soils through transformation of previously published data. Multiple linear regression analysis is used as a tool to relate the parameters to soil characteristics by selection of the statistically significant soil variables. The resultant regression equation is useful in attempting to predict these parameters and changes in hydraulic conductivity from a given SAR.

Analysis of Permeameter Information

Permeameter Filter Analysis

Analyses of solution extracts made from the fiberglass matting used in packing the permeameters showed that no adverse ion concentrations were present. Average values of four fiberglass samples of the size used in the permeameters showed sodium concentrations of 4.2 mg/l

(0.23 meq/l), calcium at 1.2 mg/l (0.06 meq/l), magnesium at 0.4 mg/l (0.03 meq/l), and EC at 0.015 mmhos/cm.

Leachate Analysis

Effluent from the columns was analyzed to examine changes from the originally applied solution and to aid in selection of equilibrium values for hydraulic conductivities. Samples were taken daily for the first three days, decreasing to every two days, and then to twice weekly after 10-14 days from the start of testing. Because of the large number of permeameters (36) in operation at one time, sample analyses were not completed during the tests to provide indications of equilibrium. Analysis of pH, electrical conductivity (EC), and sodium and calcium concentrations were made for the first series of tests, while only EC was reported for the second sequence.

The pH of the solution leachates for the first test series changed little for a particular soil at a given SAR over test periods of up to 78 days. pH for all soils was measured at SAR levels of 65, 100, and ∞. pH generally ranged from 6.5 to 7.0 at the start and values were rarely observed to move higher than one pH unit above the initial value for the test period. Grabe loam and Pima clay loam were exceptions. Those soils had a higher percentage of $CaCO_3$ and their pH values were from 6.8 to 7.9 at the higher SAR levels. The number of Whitehouse samples measured was too few to discern a trend.

Results of electrical conductivity (EC) measurements to determine equilibrium were useful as indicators of a general reduction in the concentration of the applied solution. Within five days from the start of flow, EC usually had been lowered to within ten percent of the expected final output concentration of 12-13 meq/l. However, examination of hydraulic conductivity values showed that equilibrium rates were not established within that time and that steady-state rates for many samples required in excess of 30 days to attain.

A comparison of sodium and calcium analyses of the leachate was helpful in determining the equilibrium status of the soil columns. The individual sodium and calcium concentrations in milliequivalents per liter were compared with the input composition and summed to find an approximate total solution concentration. Calculation of thirty-day and final SAR values was made for comparison with input SAR.

Table 6 shows the results for two of the soils whose output solution was analyzed at all SAR levels. Mohave sandy loam measurements show final sodium concentrations within five percent of the applied solution amounts except for SAR 10 which was slightly higher. Calcium values were near applied concentrations through SAR 20. However, at the higher SAR solutions, final concentration values remained relatively high (average [Ca] = 0.78 meq/l) even though applied calcium concentrations were extremely low or zero. For this soil, the final output SAR values for all applied solutions of SAR 35 or greater averaged only 20, with the highest being 23.1.

The results of the trials on Pima clay loam also showed high final calcium concentrations. Although final sodium concentration varied within 13% of applied amounts, final calcium was high at all SAR levels with the average for SAR 35 and above being 2.26 meq/l. By

Table 6. Comparison of Input and Output Solution Concentrations and SAR for Pima and Mohave Soils.

Soil	Input SAR[a]	30-Day SAR[b]	Final SAR[c]	Initial Sodium[d]	Final Sodium	Initial Calcium[d]	Final Calcium	Final C_T
Mohave sandy loam	0	0.0	0.0	0.00	0.02	12.50	10.94	11.0
	5	6.1	5.4	7.72	8.05	4.76	4.52	12.6
	10	13.7	12.1	10.36	12.14	2.14	2.02	14.2
	20	21.9	18.6	11.80	12.23	0.70	0.86	13.1
	35	19.5	19.0	12.25	12.18	0.25	0.82	13.0
	50	17.1	23.1	12.38	12.38	0.12	0.58	13.0
	65	16.1	20.0	12.43	11.92	0.07	0.71	12.6
	100	14.3	16.8	12.46	11.75	0.04	0.97	12.7
	∞	16.3	19.8	12.50	12.62	0.00	0.81	13.4
Pima clay laom	0	0.0	0.0	0.00	0.04	12.50	10.94	11.0
	5	6.2	5.1	7.72	7.77	4.76	4.71	12.5
	10	8.4	8.6	10.36	10.14	2.14	2.81	13.0
	20	10.0	10.7	11.80	11.40	0.70	2.27	13.7
	35	9.9	11.1	12.25	11.70	0.25	2.23	13.9
	50	12.4	12.3	12.38	11.92	0.12	1.89	13.8
	65	7.6	10.9	12.43	11.44	0.07	2.22	13.7
	100	8.8	10.6	12.46	10.84	0.04	2.10	12.9
	∞	6.6	9.6	12.50	11.31	0.00	2.81	14.1

[a] Initial total concentration = 12.5 meq/l.

[b] SAR calculations made using sodium and calcium only; no analysis made for magnesium.

[c] Test length 65-77 days (average 72 days).

[d] All concentrations in meq/l.

comparison, applied calcium concentration for these same levels ranged from zero to 0.695 meq/1. Final SAR values calculated from the sodium and calcium analyses show no SAR higher than 12 for this soil (Table 6).

The final, relatively low, output SAR values for high applied SAR levels were assumed a result of initial calcium carbonate amounts present in these alkaline soils. Therefore, final output SAR was compared with percentages of $CaCO_3$ for all soils for the higher levels of applied SAR (Table 7). The results show a high correlation at the three SAR levels compared. The correlations are significant at the five percent level and output values at the SAR 100 and SAR 65 application levels are also significant at the one percent level. Therefore, it can be assumed that the final lower SAR levels obtained are due to the continuing influence of calcium carbonate in the soil.

In summary, the results of the output leachates show that calcium levels remain high after 30 days and even through the end of the test period. Therefore, the final SAR levels for all soils tested rately are above that of SAR 20 and never above SAR 25, even though some input solutions are very high in sodium relative to calcium. These high calcium outflow values were attributed to the effect of calcium carbonate present in the soil. However, with high calcium output levels, sealing of the soils was still observed to be highly effective for higher SAR input levels, as will be shown later.

Experimental Hydraulic Conductivity

Monitoring of effluent flow rates for hydraulic conductivity calculations was begun immediately after wetting with a solution of a

Table 7. Correlation of Soil Calcium Carbonate Percentages with Final SAR Levels.

Soil[a]	Percent $CaCO_3$	Final Output SAR[b]		
		SAR 65	SAR 100	SAR ∞
Anthony	0.48	22.8	19.0	25.4
Grabe	6.55	12.7	11.1	14.4
Mohave	0.73	20.0	16.8	19.8
Pima	6.00	10.9	10.6	9.6
Vinton	1.85	19.0	17.0	23.0
Correlation coefficient (r)[c]:		-0.967	-0.976	-0.884

[a] Whitehouse not compared; only small outflow volume recorded and equilibrium not approached.

[b] Values are final measurements made on columns leached with SAR 65, 100, and ∞; C_T = 12.5 meq/l.

[c] A value of r is significant at 5% and 1% levels for $|r| > 0.878$ and $|r| > 0.959$, respectively.

particular composition. The time required for soil saturation and outflow measurement varied greatly. Vinton soils began discharging effluent within 90 minutes of application. At the other extreme, Whitehouse clay required 18-23 days to begin flow. Most soils, however, completed saturation within two days from initial solution application.

Measurements of effluent rate were made several times daily during the initial days of the experiment. After the rate of change of column discharge had nearly stabilized, readings were usually taken daily for the remainder of the test period. Measurements were continued for an average of about 72 days from the date when flow first started.

To facilitate examination of the hydraulic conductivity results, the data for all soils were plotted for graphical observation. Figures 7-12 show hydraulic conductivity values found for one soil, Anthony sandy loam, at SAR's 0, 5.2, 10.8, 26.4, 65, and 100.

The lower SAR values (Figures 7 and 8) show the apparent effects of air displacement described by Allison (1947). Rising values of conductivity were attributed by that author to entrapped air being dissolved and removed by the solution. Allison described the effect as being present only in soils wetted from the surface downwards. In this experiment, soils were wetted upwards, using deaerated water, but the results indicated significant amounts of air were still remaining after several days to block passage of the percolating solution. Surface tension and capillarity effects in the small pores within the tightly packed permeameters prevent displacement of entrapped air because the liquid is at a lower pressure than the gaseous phase. Until the air is

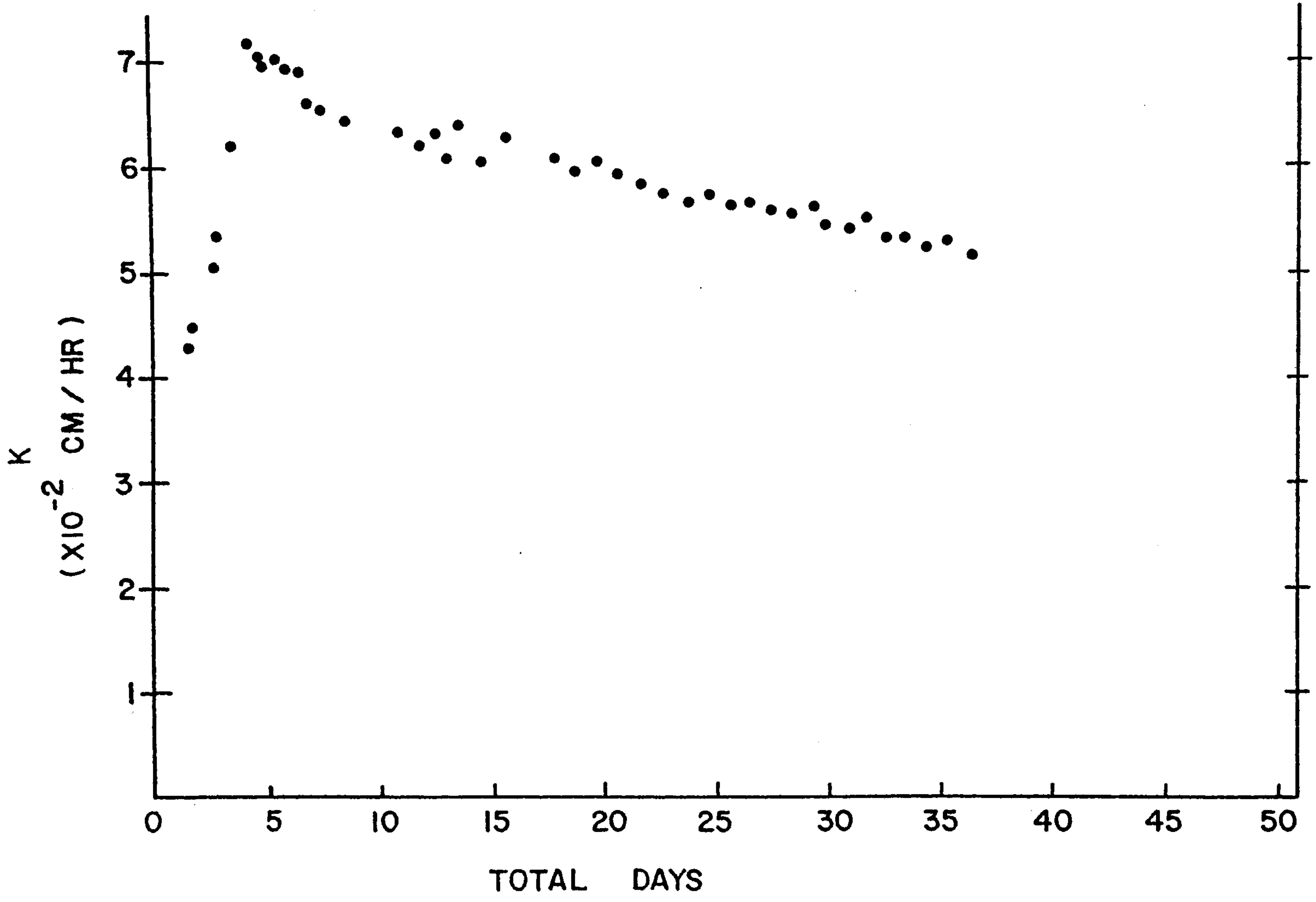


Figure 7. Plot of Hydraulic Conductivity for Anthony Sandy Loam Soil Using Water of SAR 0, C_T = 12.5 meq/1, $HgCl_2$ Added.

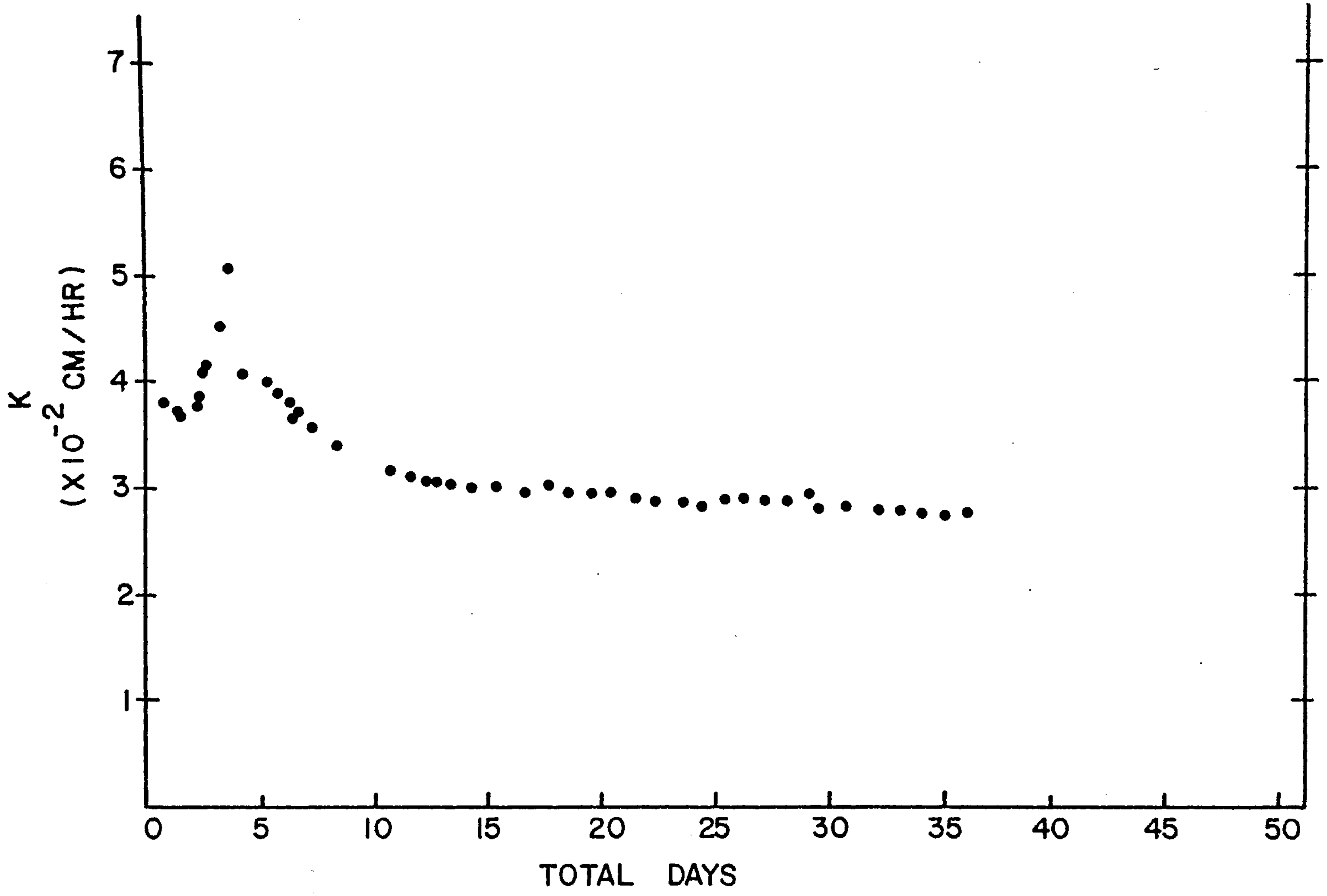


Figure 8. Plot of Hydraulic Conductivity for Anthony Sandy Loam Soil Using Water of SAR 5.2, C_T = 12.5 meq/1, $HgCl_2$ Added.

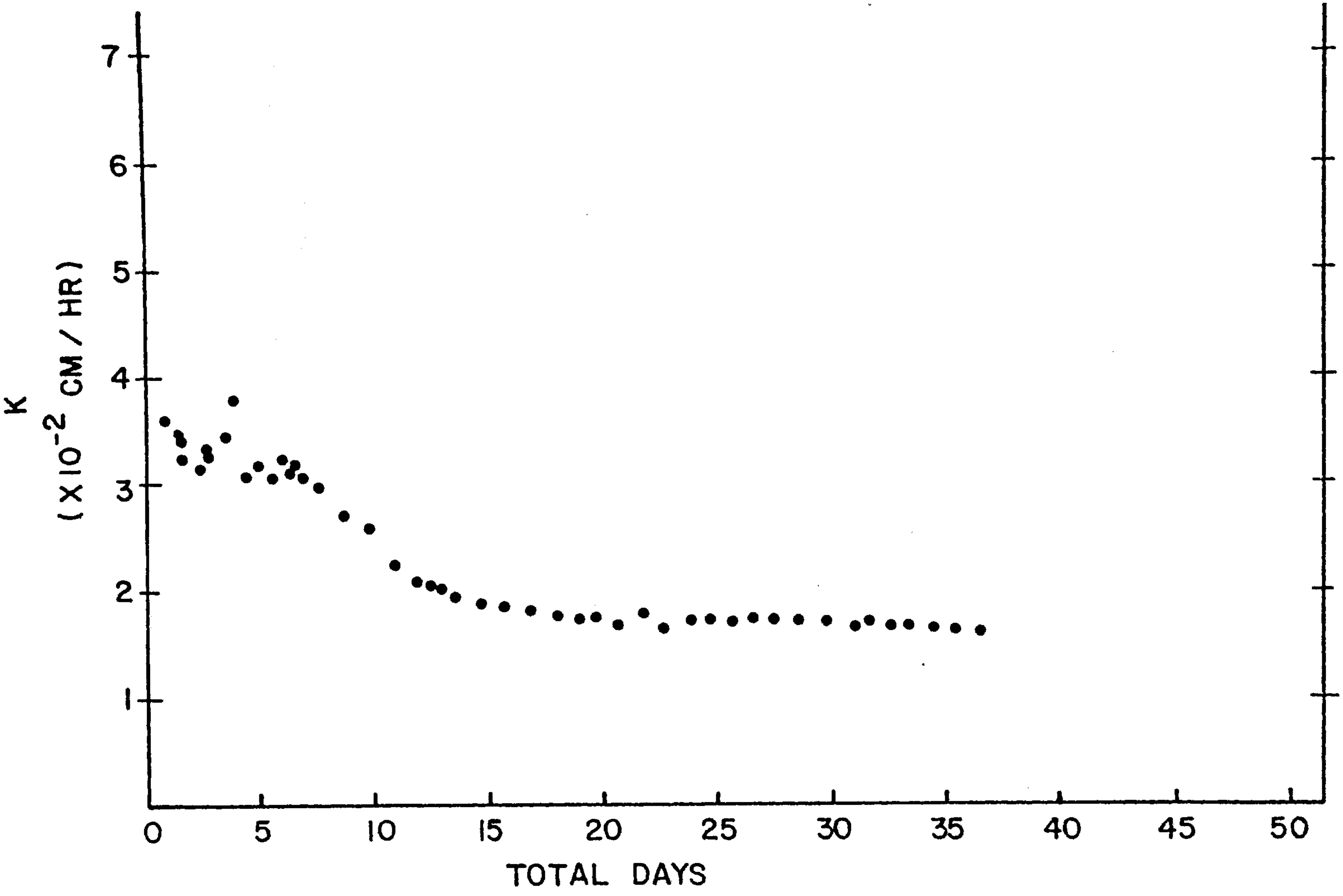


Figure 9. Plot of Hydraulic Conductivity for Anthony Sandy Loam Soil Using Water of SAR 10.8, C_T = 12.5 meq/1, $HgCl_2$ Added.

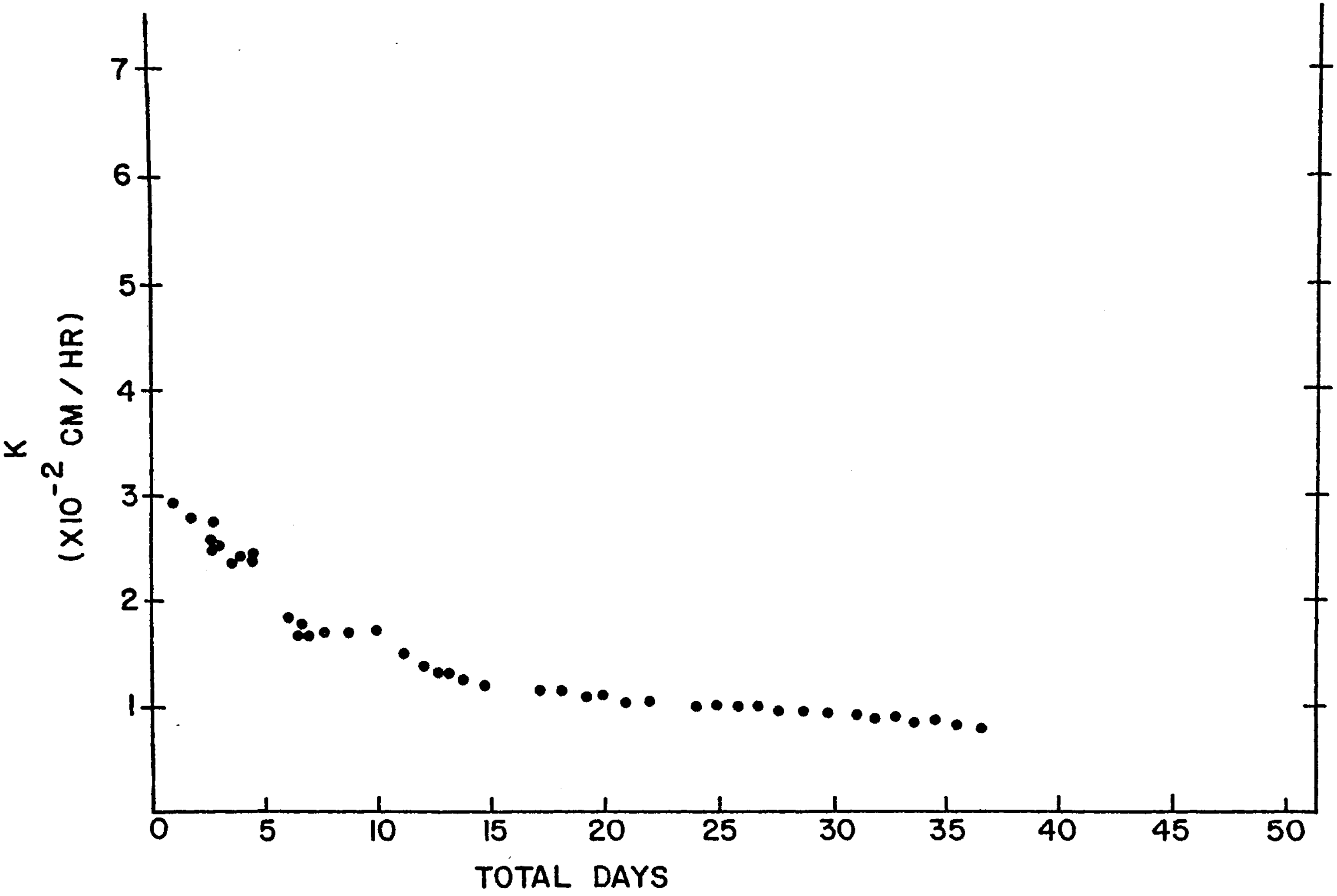


Figure 10. Plot of Hydraulic Conductivity for Anthony Sandy Loam Soil Using Water of SAR 26.4, C_T = 12.5 meq/1, $HgCl_2$ Added.

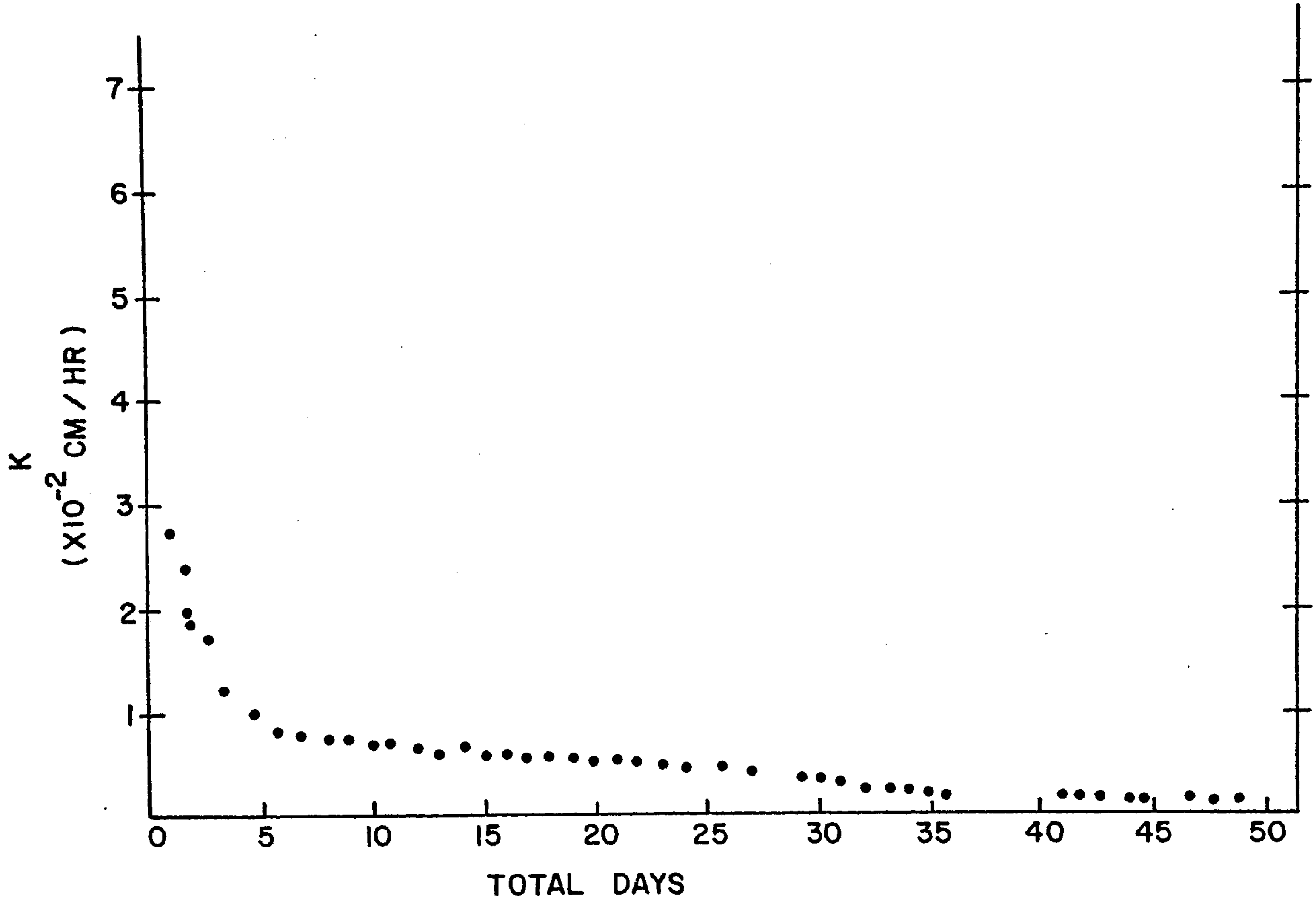


Figure 11. Plot of Hydraulic Conductivity for Anthony Sandy Loam Soil Using Water of SAR 65, C_T = 12.5 meq/1, No $HgCl_2$ Added.

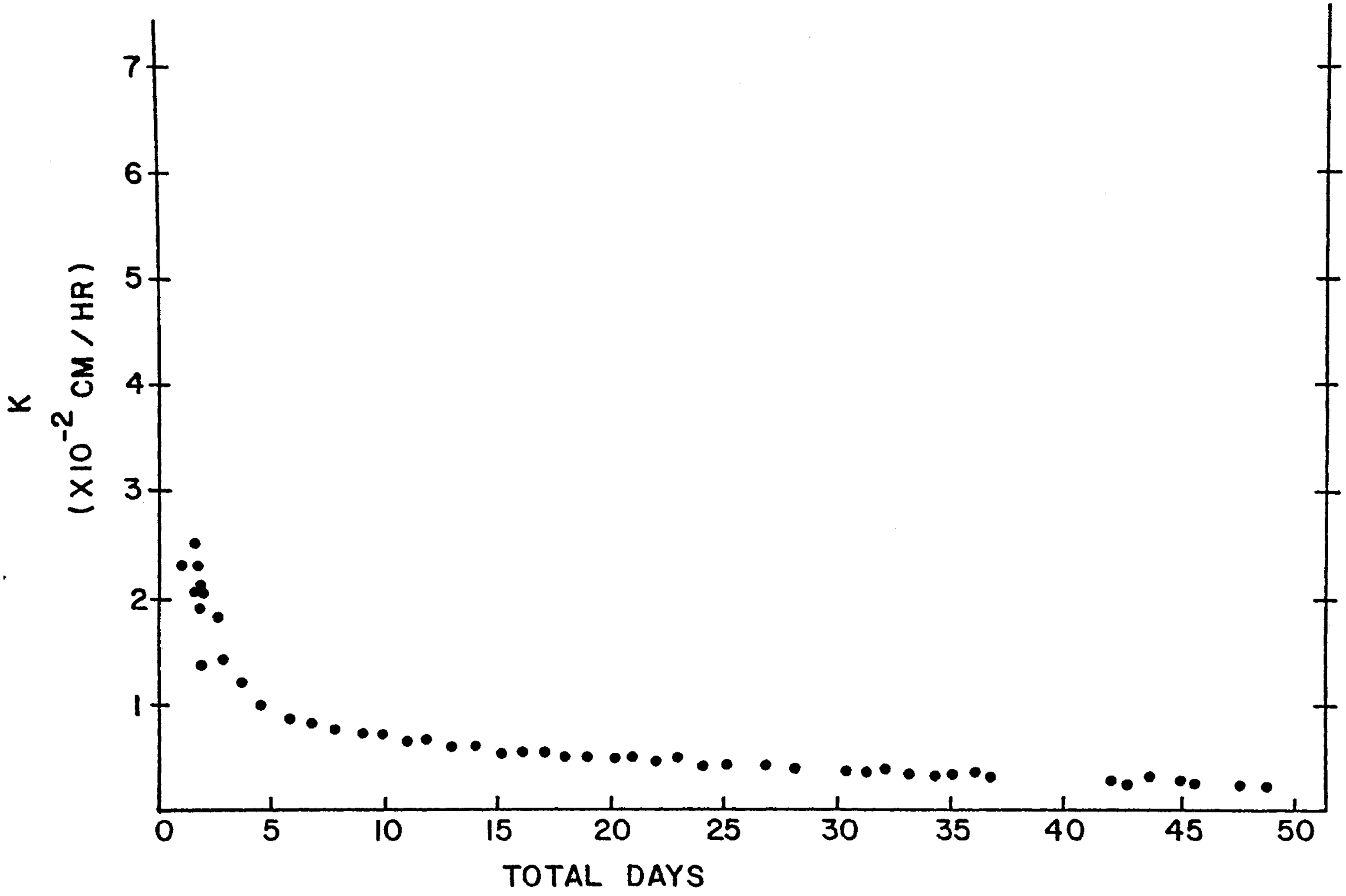


Figure 12. Plot of Hydraulic Conductivity for Anthony Sandy Loam Soil Using Water of SAR 100, C_T = 12.5 meq/1, No $HgCl_2$ Added.

dissolved in the solution, development of maximum hydraulic conductivity is prevented. For the solutions of SAR = 0 and SAR = 5.2, this occurs about the fourth day. The SAR 10.8 solution (Figure 9) may also show this effect but the initial points are too diverse for a definite conclusion.

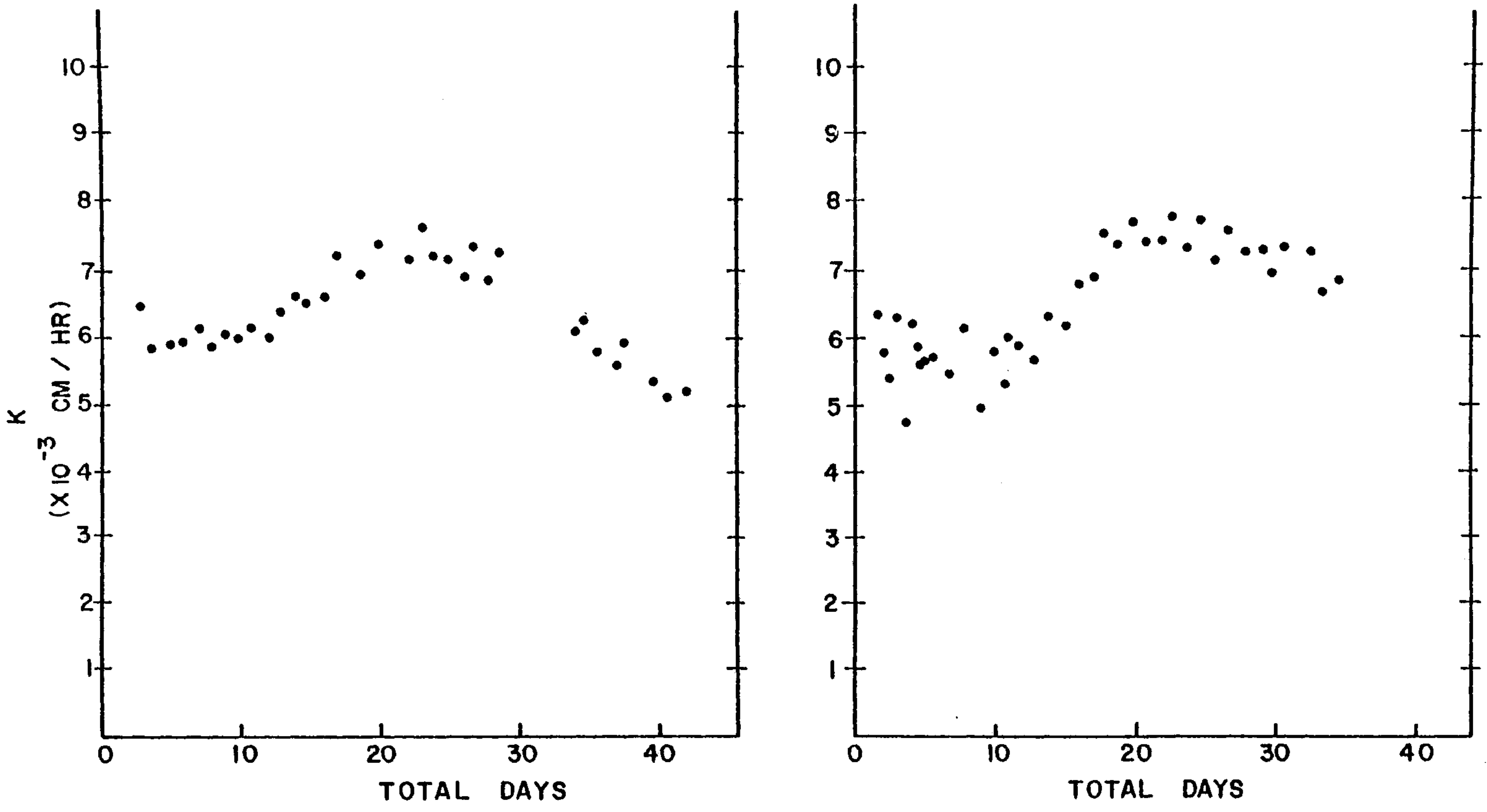
An earlier phase, described by Allison (1947) as being due to initial structural breakdown of aggregates, was seen only briefly with the SAR 5.2 sample (Figure 8).

The remaining samples of Anthony soil (Figures 10-12) showed immediate and continuing decreases in hydraulic conductivity with time. Allison (1947), explaining similar decreases, suggested a combination of continued physical disintegration of soil aggregates, bacterial clogging of pores, and dispersion due to attack of microorganisms on organic material binding soils into aggregates. Anthony samples at levels of SAR 26.4 or lower were treated with $HgCl_2$ to inhibit growth at the levels shown in Table 5. The recommended level of 40 mg/l (Christiansen, Fireman, and Allison, 1946) was applied at these solution levels. Since these samples were treated at the recommended level, decreases as a result of microorganism activity during the test period were unlikely.

The tests at higher levels (Figures 11 and 12, SAR $\geq$ 65) were part of the initial series run without any microbial growth inhibitors. Gray and dark brown-black bactieral or fungal matter appeared in the outlet tubing before completion. The Anthony soil sample leached with SAR 65 solution experienced a second, but less rapid, decrease of conductivity that was attributed to clogging. This decrease began about day 27 and continued until day 36, when a constant and final hydraulic conductivity value was maintained. The test at a level of SAR = ∞ for the Anthony soil produced a duplicate of the curve at SAR = 100 (Figure 12) and is not shown here.

Some of the other soils tested showed similar hydraulic conductivity decreases between 25 and 35 days after beginning flow that were possibly caused by microbial clogging. These included Grabe at SAR 100; Mohave at SAR 10; Pima at SAR's 0, 5, 10, and 20; Vinton at SAR's 65 and 100; and Whitehouse at SAR 50. None of these tests were run using $HgCl_2$. A second test of the Pima soil at SAR 5 made using $HgCl_2$, although not run past 35 days, did not show the secondary decreases experienced with the earlier Pima SAR 5 test (Figure 13).

The above discussion was the basis for two conclusions reached regarding conditions observed in the study. First, when decreases in hydraulic conductivity occur immediately following removal of trapped air from the samples, these decreases are primarily the results of physical structural changes in the packed columns due to either moisture interacting physically with the soil particles and chemically with the previously deposited salts, or to the sharp effect that increasing solution SAR levels has on swelling and dispersion in some soils. Secondly, although microbial action occurs in soils untreated to prevent growth, the effects are secondary to decreases caused by swelling and dispersion in the expansive soils until at least 25-35 days after beginning of permeameter testing. Since individual permeameters were used at each SAR instead of one soil sample being leached with varying SAR solutions,



(a)

(b)

Figure 13. Hydraulic Conductivity (K) for Pima Clay Loam Leached with a 12.5 meq/l, SAR = 5 Solution. -- (a) Without $HgCl_2$; and (b) containing $HgCl_2$.

the effect of any conductivity reduction due to growth should be distributed equitably over all untreated samples in the first 25 days of testing. These conclusions, believed valid for the above conditions, are important because without them microbial action in the initial days becomes an extremely important factor in the reduction of conductivity that may mask reductions resulting from other causes.

Selection of Representative Hydraulic Conductivity Values

Examination of the chemical results and plots of hydraulic conductivity versus time was expected to provide an indication of the completeness of cation exchange and the arrival of steady-state conditions. Inspection of results showed this not to be the case for some soils at either 30 days after the start of testing or for completion at 62 to 78 days. As discussed in a preceding section, chemical measurements showed relatively high calcium, low SAR values extending throughout the experiment. Graphical representation of the hydraulic conductivity showed decreases with time for most soils as calcium continued to be removed. However, conductivity changes were much slower than recorded for the first few days. This is illustrated in Figures 7-13 for the Anthony sandy loam soil. In addition, the influence of microorganisms in the later days produced further decreases in some soils that could be confused with lowering of hydraulic conductivity due to solution effects alone.

To overcome these effects and to allow comparison of approximate steady-state conductivities for the same soil at different SAR applications, hydraulic conductivities were taken from the hydraulic conductivity versus time plot at the day where the curvilinear portion of the graph first changed to produce an approximate, although still decreasing, straight line. Anthony sany loam soil, at an applied solution of SAR 5 (Figure 8), provides an example. A hydraulic conductivity of 3.0×10^{-2} cm/hr at day 14 was chosen representative at this SAR using the above criterion. The curves for some other soils had greater scatter but the procedure was used successfully to approximate steady-state hydraulic conductivity. Values of hydraulic conductivity for each soil at each SAR are presented in Table A.1 (Appendix A) and plotted in Figures A.1-A.5 of Appendix A.

Plotting of hydraulic conductivity versus SAR showed that, for some measurements, conductivity changes with increasing SAR of the input solution were not always decreases (Figures A.2-A.4). Therefore, a correction for changes in hydraulic conductivity as a result of differences in packed bulk density was attempted. The method utilized was the Kozeny-Carman equation (Hillel, 1971) relating porosity (calculated using bulk density information) to changes in permeability. However, coefficients of variation for measurement of packed bulk density values between samples for each individual soil were low (0.8 to 1.9 percent). Application of the bulk density correction to the soils showed only slight improvement to the hydraulic conductivity. Therefore, corrections for small differences in packing bulk densities were not used.

Reversibility of Sealing

The packed columns of Vinton loamy sand, originally leached with solutions of SAR 0 through SAR ∞, were chosen to examine the reversi bility of hydraulic conductivity decreases. Values of hydraulic conductivity (K_0) for sodium-free solutions were almost ten times greater for Vinton soils than were rates for the next highest soil, Anthony sandy loam, and allowed a more rapid approach to equilibrium than with the other soils. All solutions included concentrations of $HgCl_2$ as given by Table 5. As the tests lasted over 90 days, these precautions taken to prevent eventual microbial growth became important.

A ten-day treatment of a sodium-free solution (SAR 0) at C_T = 12.5 meq/l applied to the two Vinton soil samples previously leached with a solution of SAR = 20 almost tripled the final rates (to approximately $9x10^{-2}$ cm/hr). However, even this rate was less than 20 percent of the rate ($5.3x10^{-1}$ cm/hr) for the sample leached originally with a SAR = 0 solution. Only small rate increases occurred when other Vinton samples, originally leached with solutions of SAR 35 and SAR 50, were treated for ten days with sodium-free solutions. The new rates quickly stabilized and never rose above 0.13 cm/hr or about 25 percent of K_0 for the Vinton soil.

As a final test for reversibility, all Vinton samples were leached with a calcium-free solution for an additional 20 days, followed by ten days of a sodium solution. Figure 14 shows the result for the soil originally leached at SAR = 0. The hydraulic conductivity rates decreased to about $2.6x10^{-2}$ cm/hr, about 5% of the original. After

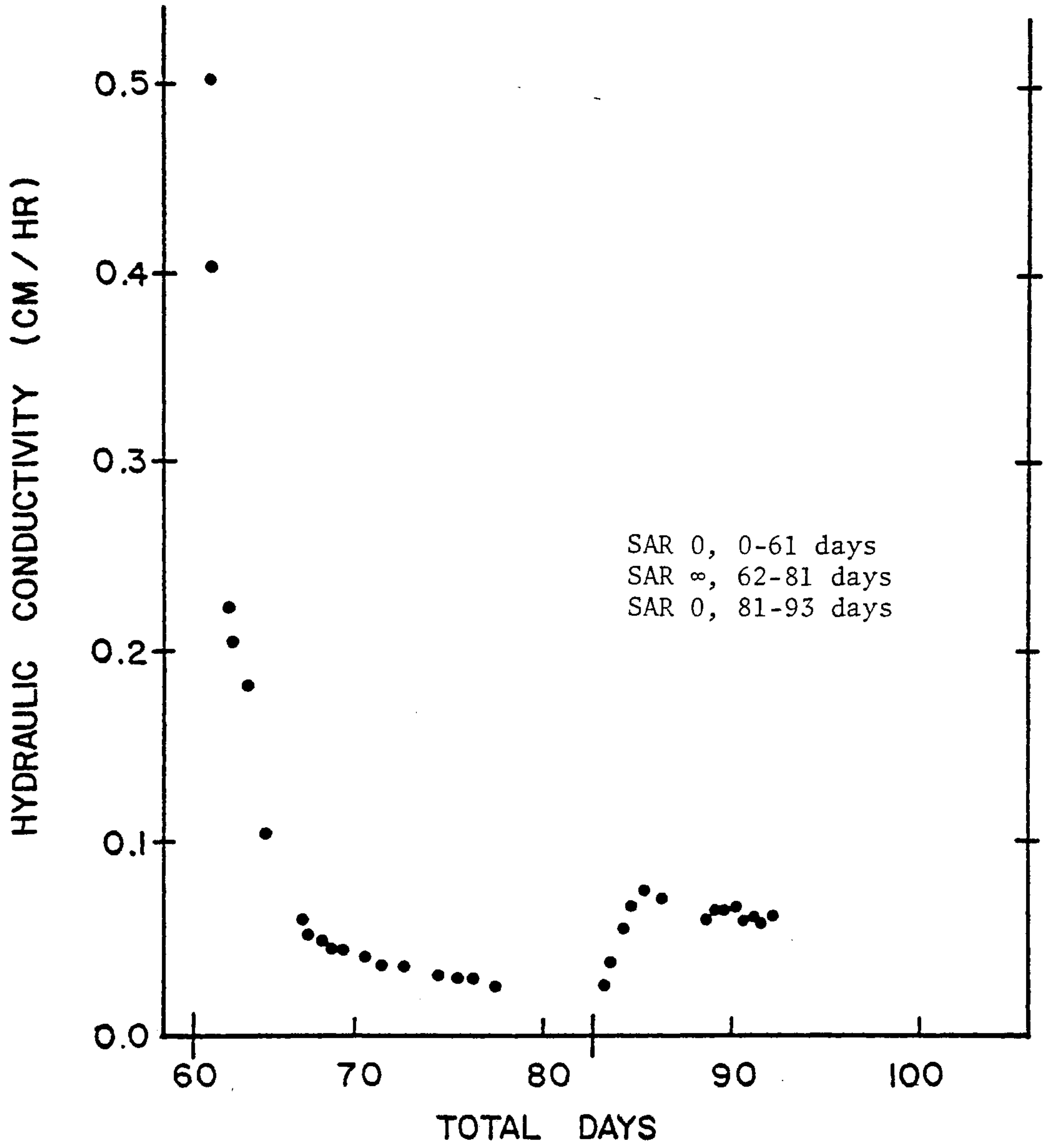


Figure 14. Hydraulic Conductivity of Vinton Loamy Sand Leached at a Concentration of 12.5 meq/l and Varying Sodium Levels Showing Non-Reversibility of Sealing.

reapplication of a SAR = 0 solution, a small increase in rates occurred followed quickly by stabilization at approximately 7.0×10^{-2} cm/hr, which is less than 15% of the original value of about 0.53 cm/hr. The other Vinton samples show similar results after reapplication of sodium-free solutions.

For Vinton soils, the results of hydraulic conductivity decreases are non-reversible and sealing is permanent under these conditions if saturation is continuous and not interrupted by drying. Reduction of conductivity was most likely produced by dispersion of the colloidal particles causing clogging, and blockage of conducting pores by movement of the dislodged silt particles. It is hypothesized that swelling was a minor factor in permanently reducing hydraulic conductivity in this soil. However, the effect of swelling in weakening interparticle bonds to allow migration of particles is likely to be considerable.

The outcome of the reversibility test on this soil is similar to that reported by McNeal (1965) for four of the seven soils tested by him. Four souls recovered under 25 percent of their original hydraulic conductivity, while the fifth recovered up to 44 percent. A sixth soil, Gila (high in montmorillonite), recovered up to 87 percent. The seventh soil, Aiken, had only small reductions (< 10%) in K at all levels, but recovered none of these. The above conclusions regarding the reversibility of Vinton loamy sand conform with the explanation of sealing presented by McNeal (1965) for his results.

Determination of the Experimental Parameters

The hydraulic conductivity results from the present study were transformed to linear form as discussed earlier for use with Equation (14) to determine the parameters c and n by regression analysis:

$$\log \left(\frac{1}{K_R} - 1 \right) = \log c + n \log (\mathrm{SAR}) \qquad (14)$$

When values of K_R are close to 1.0, transformations to Equation (14) produce a disproportionate effect on the regression. For this reason, it was decided not to use values of $K_R \geq 0.975$. Likewise, values of SAR = 0 and SAR = ∞ cannot be used. The linear regression results for the soils are presented in Table 8, with the exception of Whitehouse clay loam. The values of the correlation coefficient for the five soils are quite high, ranging between 0.85 and 0.99.

Only several values of K for the Whitehouse clay loam were able to be transformed using the above criteria for use in Equation (14). Also, K at SAR 65 was double that for SAR 50 and, therefore, relative conductivity experienced an apparent increase with SAR. Hydraulic conductivities at all other levels average 2.4×10^{-4} cm/hr. These small values make the reductions at SAR 50 and 65 subject to experimental error such as evaporation losses from the graduated cylinder. Any further attempt at analysis of conductivity reductions for Whitehouse samples would be meaningless.

Some curves originally produced by the c and n values shown in Table 8 were poor and indicated difficulty in attempting to fit a curve to the slightly irregular conductivity values produced by the use of

Table 8. Results of Linear Regression Analysis of the Transformed Variables Log (SAR) with Log ($1/K_R - 1$) for the Leached Soils.

Soil	Number of SAR Values in Regression	Regression Coefficients		Correlation Coefficient (r)	Standard Error of Estimate S(x,y)
		log c	n		
Anthony sandy loam	5	-0.427	0.742	0.99	0.06
Grabe loam	5	-0.980	0.874	0.99	0.04
Mohave clay loam	7	-1.060	1.022	0.98	0.10
Pima clay loam	8	-0.669	0.482	0.85	0.14
Vinton loamy sand	5	-1.935	1.966	0.91	0.30

individual soil permeameters for each applied SAR level. Some soils show one or more points with a value of K higher than at a preceding SAR. This was more likely to be true especially at higher input SAR levels. Pima clay loam, for example, had an unusually high value at SAR 50.

The inclusion or exclusion of poorly fitted points in Equation (14) can produce a large difference in values of log c and n generated and, therefore, on the resulting curve produced using the c and n values. Inclusion of values of relative hydraulic conductivity (K_R) less than 0.01 or greater than 0.975 were avoided since points outside this range had excessive influence on c and n due to the nature of the logarithmic transformation performed on K_R using Equation (14).

Removal of several experimental points to produce a better curve could be justified after consideration of the results of the chemical analyses. The analyses of output solutions for the leached soils, presented earlier (Table 7) show that final output SAR levels for all soils were not greater than SAR 25 at the input levels of SAR 65 or higher, but that sealing had still effectively taken place. Examination of hydraulic conductivity data shows that for most soils the major decreases in conductivity had occurred with input solutions in the range of SAR 0 to 30. Mohave, Pima, and Vinton soils in particular show essentially constant values of hydraulic conductivity at SAR input values of 30 or greater. This prevents a good curve fit to the relative hydraulic conductivity data produced at lower SAR levels. When the Mohave, Pima, and Vinton soils are re-examined without inclusion of higher SAR values, a better fit at the lower, more important SAR values is produced without causing large increases in error at higher SAR levels. The adjusted results are given in Table 9.

Hydraulic conductivities determined by McNeal (1965) and Naghshineh-Pour (1968) at total concentrations of 12.5 and 10.5 meq/1, respectively, for various SAR applications are presented in Tables A.2 and A.3 (Appendix A) and shown in Figures A.6-A.15 (Appendix A). These data were used together with Equation (14) for determination of the log c and n empirical parameters. The criteria discussed above for inclusion or rejection of points was also applied to these soils. The results of the regression analyses for the soils of McNeal (1965) and Naghshineh-Pour (1968) are presented in Table 10.

For the Aiken clay loam tested by McNeal (1965), a regression using only two SAR values was made and the resulting $r = 1.0$ has no meaning. Only the values for SAR = 5 and SAR = 100 were less than $K_R = 0.975$. Three of the remaining six K_R values for the Aiken soil were greater than 1.0, making a transformation of those points impossible. Nonetheless, data for this soil were included in some of the analyses which follow.

Similarly, a two-point transformation was also possible for the Nacogdoches fine sandy loam. However, use of the resulting c and n values produces continuing increases in hydraulic conductivity with SAR that were not observed experimentally. Therefore, this soil was not considered for further analysis.

Table 9. Adjusted Results of Linear Regression Analysis of the Transformed Variables Utilized in Producing K-SAR Curves for the Leached Soils.

Soil	Number of SAR Values in Regression	Regression Coefficients		Correlation Coefficient (r)
		log c	n	
Anthony sandy loam	5	-0.427	0.742	0.99
Grabe loam	5	-0.980	0.874	0.99
Mohave clay loam	4	-1.353	1.311	0.99
Pima clay loam	5	-0.900	0.741	0.92
Vinton loamy sand	3	-4.278	3.853	0.99

Table 10. Results of Linear Regression Analysis of the Transformed Variables Log (SAR) with Log ($1/K_R - 1$).

	Number of SAR Values in Regression	Regression Coefficients		Correlation Coefficient (r)	Standard Error of Estimate S(x,y)
		log c	n		
McNeal Soils					
Aiken clay loam	2	-1.434	0.063	1.00	0.00
Gila clay	7	-1.844	1.447	0.98	0.12
Grangeville sandy loam	5	-5.231	3.414	0.99	0.17
Oasis clay loam	6	-3.074	1.943	0.98	0.11
Pachappa sandy loam	5	-4.717	2.870	0.99	0.10
Vale silt loam	4	-1.427	0.367	0.75	0.17
Waukena clay loam	6	-4.824	3.437	0.98	0.22
Naghshineh-Pour Soils					
Beaumont clay	3	-5.428	4.080	0.99	0.04
Houston black clay	3	-4.888	3.903	0.99	0.05
Katy fine sandy loam	3	-3.426	1.864	0.96	0.06

The analysis of Vale silt loam was made using four SAR values. Hydraulic conductivity for SAR 10 was higher than at SAR = 5, causing the lowest correlation coefficient (r = 0.75) of all soils. Values for SAR's 15, 20, and 25 for this soil were greater than $K_R = 0.975$.

When values of c and n determined for each soil from experimental data are inserted into Equation (12), a relative value of hydraulic conductivity may be predicted for any desired SAR value. The predicted curves drawn using the values from Tables 9 and 10 are shown for each of the soils in Figures A.1-A.15 (Appendix A). Curves were drawn using a Wang 720C programmable calculator and a Wang 702 printer-plotter. The curves drawn in this manner can be seen to agree with the points plotted for individual SAR values.

Values of log c and n of all 15 soils have high negative correlations with each other since they interact to produce the K_R-SAR curves. The correlation coefficient, log c with n, for the five soils of the present study was r = -0.94. For the seven soils of McNeal (1965) and the total of 12 soils, r = -0.97 and r = -0.93, respectively. The addition of the three Naghshineh-Pour soils does not markedly change the correlation coefficient (r = -0.94).

A simple regression analysis of log c with n for all three studies is shown in Figure 15. If necessary, estimates of log c or n could be made from use of the calculated regression coefficients given the value of the other parameter. However, considerable error can be expected when predicted numbers are compared with the actual values.

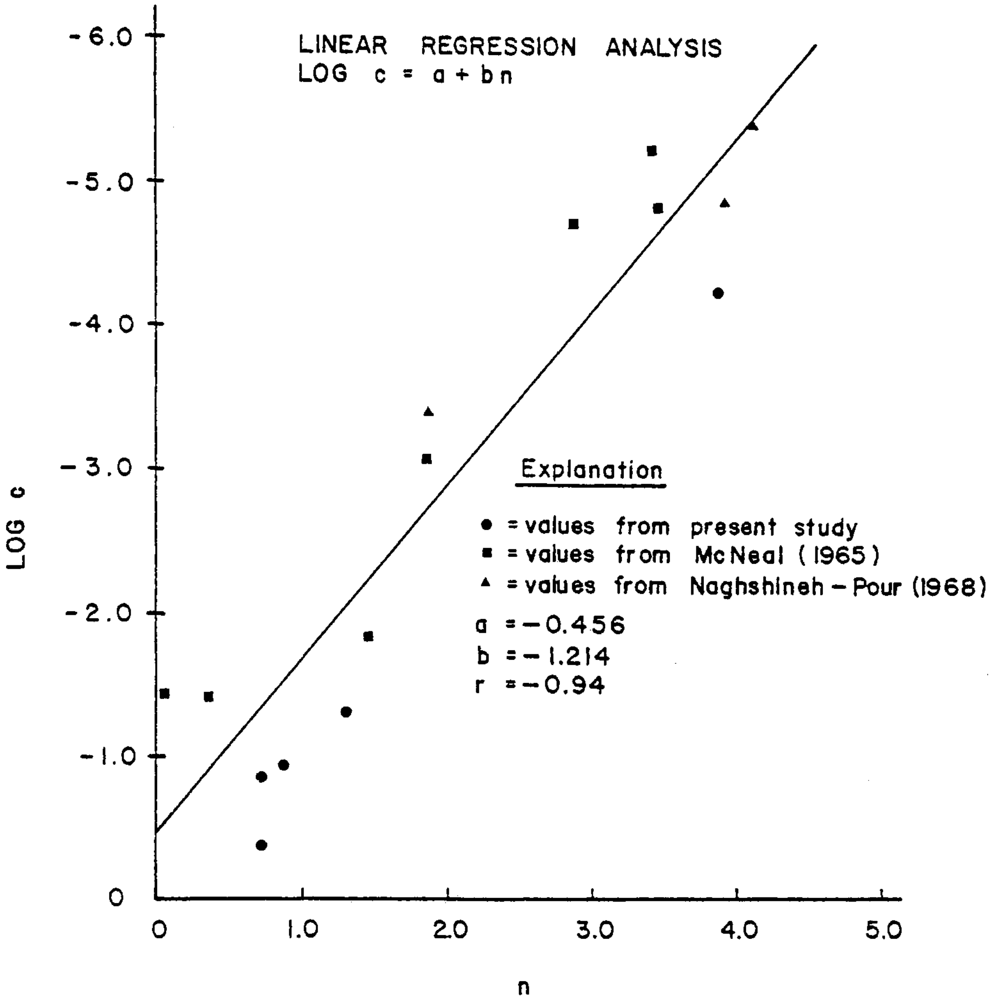


Figure 15. Regression Analysis and Graph of log c and n for 15 Soils.

Greatest differences would occur when log c is predicted from n values less than 1.0.

Prediction of Hydraulic Conductivity Changes

Method of Statistical Analysis

The physical and chemical soil properties listed in Tables 1 and 3 for all 15 soils were listed on data cards for statistical analysis using the University of Arizona CDC 6400 computer. Hydraulic conductivity (K_0) at SAR = 0 and the empirically determined soil parameters log c and n were also entered.

Additional variables were available for analysis upon completion of computer transformation of the values entered on data cards. The operations performed on the variables were logarithmic and exponential transformations. New variables were also formed by combining entered values of sand plus silt, sand plus clay, and silt plus clay, then performing further transformations as above.

The variables, both as entered and transformed, were then available for comparison with the parameters log c and n by stepwise, multiple linear regression using the method of least squares. After determination of log c and n by this method, their values may be used with Equation (12) to obtain the relative hydraulic conductivity, or, if K_0 is available, used with Equation (11) to obtain absolute values of hydraulic conductivity.

The "SPSS, Statistical Package for the Social Sciences" (Nie et al., 1975), was used for regression analysis of the variables because the program was extensively documented, used simplified data entry and transformation procedures, and allowed wide flexibility in choice of analysis method.

SPSS input provides for user choice of total number of variables to be used, F-levels to enter or remove variables, and tolerance levels. F-tests determine whether a particular variable is significant to the regression or if the regression as a whole is significant. The stepwise procedure used for entry of variables provides computer examination of F-level significance at each step for variables already in the equation as well as variables about to enter. If a newly entered variable drops the significance of any variable already in the equation below a default value, the previously entered variable (often a transformation of the newly entered variable) is automatically dropped on the next step. The tolerance level, as defined by SPSS, is the relation of variables already in the regression equation with those remaining outside the equation. Values may range from 0.00 to 1.0 and indicate amount of correspondence (multicollinearity) between supposed "independent" variables. For example, a low value such as 0.0 would indicate that an unentered variable (sand) is a perfect linear combination of the variable (silt + clay) already in the equation. Experience with the SPSS program showed that the selection of tolerance levels from 0.2 to 0.3 eliminated major problems of multicollinearity.

Output provided by SPSS is statistically complete, providing at each step coefficients of determination and correlation, regression coefficients, analysis of variance, the F-statistics, and level of significance for the total regression and each variable entered. Significance and tolerance levels for variables not selected for entry into the regression equation are also listed. Options are available that provide for comparison of actual and predicted values with graphical plotting of the residuals, calculations and tabular presentation of 95% confidence intervals for regression coefficients, and other desired statistical information. A table providing a summary of the entered variables, their correlation coefficients, F-level, and significance is a standard feature of the output.

Before continuing with the results of the analysis, several important points regarding the use of statistical techniques should be recognized.

The first, and most important, consideration is the number of individual data observations available for use in the regression. Just as only two points will produce a meaningless value of $r = 1.0$ in linear regression, too few observations will similarly produce unrealistically high correlations with the use of multiple regression techniques. The analysis of m variables using only $m+2$ observations produces values of the multiple correlation coefficient close to 1.0 and lowers significance of the remaining unentered variables to zero, causing program default at that point. Hahn and Shapiro (1966) recommend the use of at least ten more data points than unknown variables, if possible, to assure sufficient degrees of freedom for statistical analysis. Comparison of only seven soils as used by McNeal (1965) or five examined in this study (excluding Whitehouse), prevented adherence to that recommendation; however, its implications will be remembered during the following discussion.

The second point, closely related to the first, is that good correlations produced using one set of soils with a small sample size (e.g., m = 7) may not relate at all to a second similar set of soils also with a small sample size. This does not necessarily occur as a result of the experimental techniques or from differences in soils. Rather, it is due to the consequences of having a large number of available parameters (through transformations) for the computer to choose from for a best fit. It is up to the researcher to decide if the final result is meaningful or if almost random selection to provide best fit by adding extraneous terms to the regression has occurred. Selection of sufficiently high F-levels to prevent inclusion of variables that do not contribute significantly to the regression can help solve a portion of this problem. F-levels vary with the number of observations and variables already in the regression, but an entering level of F = 3 assisted in reducing irrelevant terms.

The final consideration relates to the effect the transformations themselves have on the regression. Taking logarithms of a variable, for example, reduces the variance of transformed data points. Inclusion of this variable in a least squares regression provides assurance that the sum of squares of the deviations for the transformed variable is a minimum. However, the same statement cannot be made for the sum of squares for the original variable. Therefore, conclusions about the significance of a variable must be tempered by recognition of the types of transformations made on the original variable.

Criteria used in selection of variables for the presentation of multiple regression results that follow were based on 1) the effect each variable produced as it entered the regression equation and 2) the final overall significance of the regression equation.

Initial variables were allowed to enter the equation at any significance level. Although in several cases these variables were not significant[1] at the ten percent level ($\alpha = .10$), they were allowed to enter because variables not significant at the chosen level should not necessarily be eliminated from the regression (Hahn and Shapiro, 1966). Although not individually significant at the desired level, these variables may contribute to the overall regression equation. Subsequent variables were allowed to enter into the equation if they improved the overall regression significance from the level produced by the entry of the preceding variable.

For the results of a regression analysis to be included here, the final overall significance must be better than ten percent ($\alpha = .10$). With only one exception, however, the results were more significant than this value. In most cases, the level of significance was better than five percent.

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[1] At a ten percent level of significance, the probability that there is no correlation between two variables (i.e., $r = 0$) is 0.10. The term "significant" used without a percent modifier commonly is used to indicate the five percent level while the term "highly significant" refers to the one percent level. The symbol used to denote a statistical level of significance is the Greek letter α.

The above requirements prevented inclusion in the regression equation of large numbers of variables. The effect of these variables together with the small sample size available would be to cause F-levels to increase to unrealistic levels without actually contributing in a meaningful way to the prediction of results using the method. The entry of spurious variables into the regression still remained a possibility, however. By definition, at a ten percent significance level, one out of every ten variables will be entered as a result of chance alone. An increase in the number of sample observations available would greatly improve the likelihood that the variables entered as truly significant.

Correlation of Original Variables

As part of the program output of the SPSS regression procedure, simple correlation coefficients of the original, untransformed variables with each other are available for examination. These are presented in Tables B.1-B.6 of Appendix B for all soils and Tables C.1-C.3 for alkaline soils. The characteristics that correlate with the chemical variables at a five percent level of significance or higher are shown in Table 11 for all soils and in Table 12 for soils containing $CaCO_3$. These significant correlations among variables should be remembered during interpretation of the MLR results to be presented.

Transformations, such as taking logarithms, squares, or cubes of the chemical variables, further enhance chances of correlation among the soil variables since a relationship may not be linear until one (or both) variables are transformed. These correlations, also produced as a part of SPSS output, are not presented here.

Table 11. Correlation of Soil Chemical Variables with Soil Properties at a Five Percent Level of Significance.

Chemical Variable[a]	Soil Group[b]	Soil Properties[c]
Electrical conductivity (EC_e)	A	Organic material, $CaCO_3$
	B	$CaCO_3$, silt
	E	$CaCO_3$, silt, ESP
Cation exchange capacity (CEC)	A	Sand, silt, $CaCO_3$, bulk density
	B	Bulk density
	C	Organic material, clay, sand
	D	Sand
	E	Bulk density
	F	Sand, clay, organic material
Exchangeable sodium percentage (ESP)	A	None
	B	pH
	C	None
	D	pH, silt
	E	pH, silt, EC_e
	F	Silt, pH
pH	A	None
	B	ESP, organic material
	C	None
	D	ESP
	E	ESP, organic material
	F	Organic material

[a] EC_e and bulk density not available for Naghshineh-Pour (1968) study.

[b] Soil group: A, 5 soils (this study); B, 7 soils (McNeal, 1965); C, 8 soils (5 this study plus 3 Naghshineh-Pour, 1968); D, 10 soils (7 McNeal, 1965, plus 3 Naghshineh-Pour, 1968); E, 12 soils (5 this study plus 7 McNeal, 1965); F, 15 soils (5 this study, 7 McNeal, 1965, plus 3 Naghshineh-Pour, 1968).

[c] Properties listed in decreasing order of significance.

Table 12. Correlation of Chemical Variables with Soil Properties at a Five Percent Level of Significance for Soils Containing $CaCO_3$.

Chemical Variable[a]	Soil Group[b]	Soil Properties[c]
Electrical conductivity (EC_e)	A	Organic material, $CaCO_3$
	G	$CaCO_3$, silt
	H	$CaCO_3$, silt, ESP, sand
Cation exchange capacity (CEC)	A	Sand, silt, $CaCO_3$, bulk density
	G	Bulk density
	H	Bulk density, sand, clay, pH
	I	Clay, sand, organic material
Exchangeable sodium percentage (ESP)	A	None
	G	None
	H	pH, silt, EC_e
	I	pH, silt
pH	A	None
	G	None
	H	ESP, CEC
	I	ESP
$CaCO_3$	A	Organic material, silt, EC_e, bulk density, CEC, sand
	G	EC_e
	H	EC_e, organic material
	I	Organic material, sand

[a] EC_e and bulk density not available for Naghshineh-Pour (1968) study.

[b] Soil groups: A, 5 soils (this study); G, 6 soils (McNeal, 1965); H, 11 soils (5 this study plus 6 McNeal, 1965); I, 12 soils (5 this study plus 6 McNeal, 1965, plus 1 Naghshineh-Pour, 1968).

[c] Properties listed in decreasing order of significance.

Results of Multiple Regression Analysis

The derived parameters log c and n were compared using various combinations of soil groupings to determine which soil characteristics are most significant in predicting these parameters. The parameter log c instead of c was used in regression analysis since transformation of c produced very small values that were difficult to compare. The results from the present study for the five Arizona soils were examined as a single group and combined with McNeal (1965) and Naghshineh-Pour (1968) to total 5, 8, 12, and 15 experimental observations. Later, the seven Western soils tested by McNeal (1965) were compared and then combined with the three Texas soils of Naghshineh-Pour (1968) for a total of 7 and 10 observations. Comparisons that include the three soils of Naghshineh-Pour do not include values of bulk density and electrical conductivity of the soil saturation extracts in the regression since these values were not available.

Alkaline soils were compared separately since soils in arid regions of Arizona and the Southwest are predominately calcareous. Of the 15 total soils available for comparison, 12 were alkaline, including the five from the present study. The results for these soils are also presented and discussed below.

Additional comparisons were made by including as a variable the steady-state hydraulic conductivity, K_0, for individual soils using a calcium (SAR = 0) input solution. This was done to evaluate the variation in results due to the different packing and wetting methods used by the different researchers. Fractional amounts were also used instead of percentage values for the variables of sand, silt, clay, ESP, organic material, and calcium carbonate. The use of fractional amounts instead of percentages prevented meaningless values of the regression coefficients resulting from exponential transformations (e.g., $e^{0.45}$ vs. e^{45} for percentage of sand in a soil).

The results of the regression analysis are presented in Tables 13 and 14 for the parameters log c and n. These tables compare the parameters against the soil variables without inclusion of K_0. Similarly, Tables 15 and 16 present results of the analyses of alkaline soils using parameters log c and n but with inclusion of K_0 as a variable.

Discussion of MLR Results

Comparisons of regression analyses from different researchers with those from a single researcher show that much better results generally are produced when data from a single researcher exclusively are analyzed. When compared in this manner, correlation of parameter log c with the soil variables (Table 13) produced good correlations for the five soils of the present study and the seven tested by McNeal (1965) (regression $r^2 = 0.92$ and 0.89, respectively). The soil combinations from different researchers had lower correlations. In addition, the ten soil combinations of McNeal (1965) and Naghshineh-Pour (1968) produced no variables to enter the equation. Entry for the first variable would have been at a level of 20 percent and later variable entry does not improve this poor significance level. The 15 combined soils of the present study, McNeal (1965), and Naghshineh-Pour (1968) also do not produce significant variables.

Table 13. Multiple Linear Regression Analysis of Parameter Log c with Soil Variables.

Parameter	Researcher	Number of Soils	Variable[a]	Regression Coefficients and Constant, a	Cumulative Correlation Coefficient (r)	Level of Significance of Entered Variable	Final Regression (r^2)	Regression Level of Significance
All Soils								
log c	Boyer	5	log(clay)	11.16	.74	.15		
			$(CEC)^3$	-3.97×10^{-4}	.99	.03		
				a = 9.82			.97	.027
	Boyer, Naghshineh-Pour	8	$(clay)^3$	-21.08	.77	.02		
				a = -1.62			.59	.025
	Boyer, McNeal	12	log(organics)	3.47	.37	.23		
			$(\rho_B)^3$	1.19	.61	.10		
			CEC	0.15	.89	.00		
				a = -2.09			.79	.004
	McNeal	7	$(silt+clay)^2$	6.99	.85	.02		
			$CaCO_3$	-9.60	.94	.07		
				a = -6.70			.89	.013
Alkaline Soils								
log c	Boyer	5	same as above					
	Boyer, McNeal	11	$(\rho_B)^3$	1.74	.41	.22		
			CEC	0.15	.82	.01		
			$(sand)^3$	-8.16	.96	.00		
				a = -10.22			.92	.000
	McNeal	6	$(silt+clay)^3$	3.23	.88	.02		
			$(CEC)^3$	2.64×10^{-4}	.98	.04		
				a = -5.62			.96	.009

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[a] Soil variable abbreviations: CEC, cation exchange capacity (meq/100 g); organics, fraction organic material; ρ_B, packed bulk density (g/cm^3); $CaCO_3$, fraction calcium carbonate; sand, silt, and clay values are fractional.

Table 14. Multiple Linear Regression Analysis of Parameter n with Soil Variables.

Parameter	Researcher	Number of Soils	Variable[a]	Regression Coefficients and Constant, a	Cumulative Correlation Coefficient (r)	Level of Significance of Entered Variable	Final Regression (r^2)	Regression Level of Significance
All Soils								
n	Boyer	5	log(clay)	-9.56	.79	.11		
			$(clay)^3$	148.58	.98	.05		
				a = -8.01			.96	.038
	Boyer, Naghshineh-Pour	8	$(organics)^3$	7.22×10^4	.71	.05		
				a = 1.53			.51	.047
	Boyer, McNeal	12	log(organics)	-1.99	.49	.10		
				a = -2.37			.24	.102
	McNeal	7	$(silt+clay)^2$	-4.04	.76	.05		
				a = 4.17			.58	.047
Alkaline Soils								
n	Boyer	5	same as above					
	Boyer, McNeal	11	$(silt)^3$	-3.70	.38	.25		
			$(\rho_B)^3$	-1.19	.53	.25		
			CEC	-.10	.79	.04		
			$(sand)^3$	7.35	.93	.02		
			log(ESP)	0.82	.97	.03		
				a = 7.99			.95	.003
	McNeal	6	$(silt+clay)^3$	-3.44	.82	.04		
				a = 3.71			.68	.044

[a] Soil variable abbreviations: CEC, cation exchange capacity (meq/100 g); organics, fraction organic material; ρ_B, packed bulk density (g/cm^3); $CaCO_3$, fraction calcium carbonate; ESP, exchangeable sodium percentage (fraction); sand, silt, and clay values are fractional.

Table 15. Multiple Linear Regression Analysis of Parameter Log c with Variables and Sample Hydraulic Conductivity, K_0, at Solution SAR = 0.

Parameter	Researcher	Number of Soils	Variable[a]	Regression Coefficients and Constant, a	Cumulative Correlation Coefficient (r)	Level of Significance of Entered Variable	Final Regression (r^2)	Regression Level of Significance
All Soils								
log c	Boyer	5	$(K_0)^3$	-10.00 a = -0.91	.98	.00	.95	.002
	Boyer, Naghshineh-Pour	8	$\log(K_0)$	-1.44 a = -3.48	.92	.00	.84	.001
	Boyer, McNeal	12	$\log(K_0)$ $(\text{organics})^3$	-1.66 7.49×10^4 a = -4.25	.70 .81	.01 .06	.66	.008
	Boyer, McNeal, Naghshineh-Pour	15	$\log(K_0)$	-1.36 a = -3.60	.77	.00	.59	.001
	McNeal	7	$(\text{silt+clay})^2$ $CaCO_3$ K_0	9.78 -11.06 0.45 a = -8.72	.85 .94 .99	.02 .07 .02	.99	.003
	McNeal, Naghshineh-Pour	10	$\log(K_0)$	-1.08 a = -3.68	.59	.07	.35	.073
Alkaline Soils								
log c	Boyer	5	same as above					
	Boyer, McNeal	11	$\log(K_0)$	-1.79 a = -4.25	.83	.002	.69	.002
	Boyer, McNeal, Naghshineh-Pour	12	$\log(K_0)$	-1.56 a = -3.96	.83	.001	.70	.001
	McNeal	6	$(\text{silt+clay})^3$ $(\text{CEC})^3$	3.23 2.64×10^{-5} a = -5.62	.88 .98	.02 .04	.96	.009

[a] Soil variable abbreviations: K_0, hydraulic conductivity (cm/hr) when leached with a calcium solution (SAR 0) at 12.5 meq/l; organics, fraction organic material; $CaCO_3$, fraction calcium carbonate; silt and clay values are fractional.

Table 16. Multiple Linear Regression Analysis of Parameter n with Soil Variables and Solution Hydraulic Conductivity, K_0, at Solution SAR = 0.

Parameter	Researcher	Number of Soils	Variable[a]	Regression Coefficients and Constant, a	Cumulative Correlation Coefficient (r)	Level of Significance of Entered Variable	Final Regression (r^2)	Regression Level of Significance
All Soils								
n	Boyer	5	$(K_0)^3$	8.79	.98	.00		
			log(ESP)	-.54	.99	.09		
				a = 0.26			.99	.005
	Boyer, Naghshineh-Pour	8	$\log(K_0)$	0.99	.84	.01		
				a = 2.70			.70	.010
	Boyer, McNeal	12	$\log(K_0)$	1.00	.50	.10		
			$(\text{organics})^3$	$-7.79\text{x}10^4$	.76	.02		
				a = 2.92			.58	.019
	Boyer, McNeal, Naghshineh-Pour	15	$\log(K_0)$	0.87	.63	.01		
				a = 2.47			.40	.011
	McNeal	7	$(\text{silt+clay})^2$	-8.55	.76	.05		
			$\log(K_0)$	-1.61	.95	.02		
			$(CaCO_3)^2$	24.84	.99	.02		
				a = 5.81			.99	.002
	McNeal, Naghshineh-Pour	10	K_0	0.21	.62	.06		
				a = 1.66			.39	.055
Alkaline Soils								
n	Boyer	5	same as above					
	Boyer, McNeal	11	$\log(K_0)$	1.11	.74	.01		
				a = 2.90			.55	.009
	Boyer, McNeal, Naghshineh-Pour	12	$\log(K_0)$	1.07	.79	.00		
				a = 2.85			.62	.002
	McNeal	6	$(\text{silt+clay})^3$	-3.44	.82	.04		
				a = 3.71			.68	.044

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[a] Soil variable abbreviations: K_0, hydraulic conductivity (cm/hr) when leached with a calcium solution (SAR 0) at 12.5 meq/l; ESP, exchangeable sodium percentage (fraction); organics, fraction organic material; $CaCO_3$, fraction calcium carbonate; silt and clay values are fractional.

Examination of parameter n in Table 14 shows a high correlation occurring only with the five soils from the present study. A smaller value resulted with the seven soils tested by McNeal (1965). No values or poor results usually occurred when data from different researchers were combined. An exception was the combination of eight total soils from the present study and Naghshineh-Pour (1968) in which 51 percent of the variation was explained by entry of just one variable.

The data were examined again for both parameters using only soils containing calcium carbonate ($CaCO_3$) with pH values greater than 7.0. Results for the parameter log c using alkaline soils resulted in improvement of individual soil variables for the six remaining soils of McNeal (1965). Improvement was also seen using the combined results for eleven soils from the present study and McNeal.

Mixed results occurred for the examination of the parameter n using only alkaline soils. Improvement was seen for the six remaining soils from McNeal (1965). However, this was offset by the elimination in the regression of all significant variables for the combined soils from individual researchers.

The superior results from a single researcher may be due to differences in experimental procedures (packing techniques, laboratory setup, chemical analyses, etc.) or, equally likely, from the small number of soil samples (5 or 7) available for examination with large numbers of variables in the regression analysis. Additional samples tested using a single experimental technique would have provided a clearer understanding of the reasons for the better results when using only data from a single source.

Since the soil columns prepared for this study were packed differently from those of McNeal (1965) and Naghshineh-Pour (1968), the approximate steady-state hydraulic conductivity, K_0, for the calcium input solution (SAR = 0) was thought to be more useful than any other single parameter, including bulk density, in characterizing the differences in conductivity decreases with SAR due to packing variation. Therefore, a second series of regression analyses that included K_0 as a variable were performed using parameters log c and n to find the most significant variables. Tables 15 and 16 present the results of this second analysis. Improvement was usually obtained for these parameters with soils from either a single researcher or combinations of data sources.

The correlation coefficient and the significance of the regression are considerably improved in most cases for the parameter log c when K_0 is included as a soil variable (Table 15). Its use with parameter log c produced significant results in all six of the soil combinations examined. The lowest correlation coefficients are for Naghshineh-Pour combinations of 10 and 15 soils. Even those, however, produce generally fair estimates of actual values when regression coefficients are used to calculate log c. Results for three of the other combinations produced correlation coefficients higher than when compared without K_0, and improvements in regression significance levels. However, the 12 soil combination of McNeal soils plus those from the current study produced a lower correlation when compared using K_0.

Parameter n together with K_0 is examined in Table 16. When soils from a single researcher were compared with soil parameter n for significance, the resulting correlations are better than $r = 0.99$, with significance better than 5 percent. It is interesting to note, however, that for the data of the current study and McNeal (1965) the variables judged significant differ; no form of the same variable is common to both analyses. Comparison of the combined soil data sources in Table 16 provides a variety of results. Only one of the four combinations has at least two variables in the equation. Final values for the cumulative correlation coefficient are not overly high (r ranges from .62 to .84) but the overall regression equations are significant at 5 percent or better.

Use of the alkaline soils with the variable K_0 to compare the empirical parameter log c (Table 15) provides no or only slight improvement in correlations from those in Table 13. The 12 alkaline soil combination that was not found significant in Table 13 is used here with log (K_0) as a variable with log c to provide a highly significant, one-step regression with $r^2 = 0.70$.

Use of K_0 as one of the variables to compare with the n parameter produced good improvement when soils of the several researchers are combined. Before use of K_0, significant correlation was seen in only two of the four possible cases. After inclusion of K_0, all cases (individually and in combinations) were significant and one of the two previously significant had increased its correlation coefficient. All final cumulative correlation coefficients for the alkaline soil comparison of n using K_0 as a variable were greater than $r = 0.74$ for any single soil set or combination of soils.

To further assist in discerning the factors that improve correlations when K_0 was used as a variable, K_0 was compared with soil variables for single researchers and for combinations of investigators. Table 17 presents the results of these comparisons. Soil texture is most important in providing correlations between soils of an individual researcher. For the combined soil observations, however, no single variable seems to predominate. ESP, CEC, pH, and organic material all appear at some time in the regression equation when differing soil combinations are tried, but are apparently not sufficiently interrelated with K_0 to appear consistently in each equation.

Summary of MLR Results

Results of the various regression analyses (excluding the variable K_0) showed clay to be the most significant initial variable influencing the parameter log c. The more common of the secondary variables to enter later in the regression was cation exchange capacity (CEC). However, bulk density (ρ_B), sand, and calcium carbonate were also significant.

Variables significant with parameter n were clay, silt, (silt + clay), and organic material. The secondary variables were clay, bulk density, sand, ρ_B, and ESP.

Table 17. Multiple Regression Comparison of Hydraulic Conductivity with Soil Properties.

Parameter[a]	Researcher	Number of Soils	Variable[b]	Cumulative Correlation Coefficient (r)	Level of Significance of Entered Variable	Final Regression (r^2)	Regression Level of Significance
K_0	Boyer	5	log(clay)	.74	.15		
			$(\text{clay})^3$	.93	.16	.87	.130
	McNeal	7	$(\text{sand})^3$	.95	.00		
			$(\text{organics})^3$	.99	.02	.98	.000
	Boyer, McNeal	12	log(ESP)	.52	.09	.26	.086
	Boyer, McNeal, Naghshineh-Pour	15	$e^{(\text{CEC})}$	.82	.00	.66	.000
log K_0	Boyer	5	log(clay)	.79	.10	.64	.105
	McNeal	7	$e^{(\text{sand})}$	.80	.03		
			$(\text{organics})^3$	.93	.06		
			log(clay)	.99	.02	.98	.003
	Boyer, McNeal	12	none	--	--	--	--
	Boyer, McNeal, Naghshineh-Pour	15	$(\text{organics})^3$	.52	.05		
			log(organics)	.73	.02	.53	.011

[a] K_0 measured for a calcium solution (SAR = 0) at a concentration of 12.5 meq/1.

[b] Variable symbols: organics, fraction soil organic material; ESP, exchangeable sodium percentage (fraction); CEC, cation exchange capacity (meq/100 g).

Estimates of the parameters log c and n after inclusion of values of K_0 in the regression equations usually were improved, especially for those soil combinations that had no significant variables entering the equation without the use of K_0. In only two cases did results for a series of soils (Boyer, McNeal using log c with all and 12 total soils) show a lowering of the predictions with use of K_0 (i.e., Boyer, McNeal using log c with 11 and 12 total soils).

When values of K_0 were made available for inclusion in regressions comparing log c, the first entered and most common variables were values of K_0 and transformations of K_0. Secondary variables were organic material, CEC, and $CaCO_3$. The variable K_0 was usually entered as the second variable in equations where it did not enter as the initial variable. An exception occurred for the six alkaline soils reported by McNeal (1965). Although K_0 was made available for entry into the regression, it did not enter and the variables and their entry position remained unchanged from Table 13.

Inclusion of K_0 as a variable in the analyses with parameter n likewise improved regression results. The primary initial variables entering were values of K_0. Secondary variables, if entered, were ESP, organic material, and $CaCO_3$. K_0 entered once as a secondary variable.

The combination of soils and parameters used in Tables 13-16 could produce a total of 40 possible regression equations with significant variables. Soil characteristics (other than K_0) entering as initial variables in regression equations and the number of times entering were: (silt + clay), 8; clay, 5; organic material, 3; and silt and ρ_B, 1. Of the 40 combinations, 20 were allowed to use K_0 as a possible variable for entry into the regression. For these 20 cases, K_0 entered 16 times, making this variable the most important initial variable.

Characteristics effective as secondary variables and number of times appearing were: CEC, 7; calcium carbonate, 3; and clay, organic material, ρ_B, sand, and ESP, 2. Hydraulic conductivity was only entered twice as a secondary variable out of the 20 combinations available. The main reason for this low number is that K_0 was entered a considerable number of times as an initial variable.

ESP was entered only once as a significant secondary variable. Nonetheless, it was observed quite often as the variable that next would be entered into the regression if the criteria for variable entry discussed earlier were relaxed. Electrical conductivity of the saturation extract (EC_e) was not entered at all as a significant variable in any of the runs. However, it could not be compared for any soil combinations involving the Naghshineh-Pour soils since that EC data was not available.

Texture is the major factor influencing values of log c and n. In most comparisons, the silt fraction, clay fraction, and silt plus clay fraction were the major variables found significant. Properties such as ρ_B and CEC that have a close relationship to texture were found to be important as secondary variables. CEC and ρ_B have good correlations with clay content for many soils (Tables B.1-B.6 of Appendix B and Tables C.1-C.3 of Appendix C). Another commonly entered variable, organic material, also related well with sand and clay for some soils and, therefore, is linked to texture. Examination of parameters with K_0 included as a variable (to compare packing techniques used by the different authors) eliminated most texture terms from the regression equation. In most cases, K_0 then becomes the most significant term.

Selection of an Empirical Prediction Equation

As a result of the above discussion, regression equations determined using the total of 11 alkaline soils (five from this study plus six of McNeal, 1965) were chosen to be most representative for predicting log c and n parameters. The parameters are then inserted into Equation (12) to produce predicted values of hydraulic conductivity relative to K_0 due to SAR changes. The correlation coefficient and significance of these particular parameters may be found from Tables 13 and 14. The use of K_0 and Equation (11) will produce absolute values of K. The expression selected as best representing the results of the current study is:

$$\begin{aligned} K = K_0\{1 &+ \exp[1.74(\rho_B)^3 + 0.15(\mathrm{CEC}) - 8.16(\mathrm{Sand})^3 \\ &- 10.22]*\mathrm{SAR}**[-3.70(\mathrm{Silt})^3 - 1.19(\rho_B)^3 - .10(\mathrm{CEC}) \\ &+ 7.35(\mathrm{Sand})^3 + 0.82 \log(\mathrm{ESP}) + 7.99]\}^{-1} \end{aligned} \quad (17)$$

with sand, silt, and ESP expressed in fractional values; CEC in meq/100 g; ρ_B in g/cm^3; and K_0 in cm/hr. As discussed previously, the use of this equation with confidence should be qualified by recognition of the assumptions involved in its derivation.

Suggestions for Further Research

The need for a greater sample size for statistical analysis has already been discussed. Additional soils selected for investigation should be packed in a uniform manner to eliminate variations in packing techniques.

Since the results showed that hydraulic conductivities were most effectively reduced between input solutions of SAR 5-25, future studies should include leaching using additional levels of SAR in this range.

The amount of organic material in the soil was found to be a significant soil property for several of the soil combinations examined. However, only estimates of actual amounts were available for the Arizona soils. More precise organic matter determinations should be made in future studies.

Different combinations of the soil properties to form new variables might be tried in future analyses. Such transformations could include sums, multiples, or division operations. However, a larger sample size is necessary for effective use of the additional transformations. A small number of observations is likely to lead only to curve fitting of points instead of finding a significant soil property or its transformation.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Hydraulic conductivity changes in soils (usually decreases) due to increasing concentrations of dissolved sodium salts in the percolating waters of a constant total concentration were found to be described by an equation which includes two characteristic parameters, c and n, introduced in the preceding sections (Equation 11). Permeameter studies were conducted at different SAR's using a solution concentration of 12.5 meq/l to determine values of these parameters for six Arizona soils.

Hydraulic conductivities for five soils were reduced 60 to 95 percent for input solutions having a maximum SAR of 25. SAR values of 10 or less produced reductions of at least 25 percent in these soils. The remaining soil (Whitehouse) had an extremely low initial hydraulic conductivity which prevented detection of changes resulting from variations in solution composition.

Chemical analyses of the leachates showed that calcium carbonate present in the calcareous soils was being dissolved slowly, preventing final output SAR values from reaching higher than SAR 20-25, although input values were as high as SAR ∞. This result did not prevent effective sealing from occurring at these high input SAR levels. Hydraulic conductivity decreases that were initially produced from increasing amounts of sodium in a solution were much more important than reductions from biological sealing as the latter became visible only after 25-30 days from the start of leaching. Application of $HgCl_2$ at 40 mg/l on some samples prevented microorganism growth.

The soil having the highest initial hydraulic conductivity was tested for reversibility of sealing. Vinton loamy sand recovered less than 20 percent of its original hydraulic conductivity from the reapplication of a sodium-free solution after 20 days of leaching with a SAR 50 solution. This result has application in the sealing of ponds by sodium salts. Sealing appears to be nearly irreversible under conditions of low total solution concentration and continuous saturation. However, reflocculation of clays and loss of seal may occur if total dissolved salt concentration is markedly increased or if the pond is allowed to dry through evaporation or withdrawal of water for use.

Selection of approximate steady-state hydraulic conductivites from permeameter experiments performed at different SAR solution levels provided data for determination of the empirical parameters for the Arizona soils. Appropriate transformations (Equation 14) were used to linearize the relative hydraulic conductivity-SAR relation for statistical regression analysis. The values of log c and n generated for individual soils were found to have good to excellent correlations with the original experimental points (Tables 9 and 10) as did the curves drawn using those parameters.

Multiple linear regression analysis was used to compare the parameters found for the present study with individual soil properties.

Values of log c and n found from this study and the data of previous studies were examined separately and then combined to find the most important soil properties for predicting hydraulic conductivities. The regression analyses showed that no single physical or chemical variable or variable transformation was common to all soils that could produce significant correlation of estimated values with actual values using the data available. However, textural terms (e.g., clay, silt, etc.) were frequently significant as regression coefficients in the equations. Analysis of values using data from a single research source always produced higher correlations than examination of the values taken from several different sources (Tables 13 and 14). Inclusion of the individual soil hydraulic conductivity, K_0, determined using a calcium solution (SAR = 0) helped improve correlations by minimizing soil column packing differences among researchers (Tables 15 and 16).

Given the current amount of information, Equation (17), determined using data for 11 alkaline soils from both the present study and McNeal (1965), has been selected as the best equation for prediction of hydraulic conductivity from changes in SAR. Insertion of values for soil properties and solution SAR into Equation (17) will provide an estimate of hydraulic conductivity at a total concentration of 12.5 meq/1. Hydraulic conductivity is absolute (cm/hr) if a value of K_0 is available; otherwise, the value calculated is relative.

As a first attempt at using easily determined soil characteristics to predict hydraulic conductivity changes, the present research has been successful. This study has outlined a method and procedures to follow to describe curves of individual soil response to increases in solution SAR. However, only partial success has been achieved in relating this response to individual soil characteristics. Additional soils, packed and leached using a standardized procedure, must be examined to produce better estimates by use of the multiple regression method.

APPENDIX A

CHARTS AND TABLES OF HYDRAULIC CONDUCTIVITY EXPERIMENTS

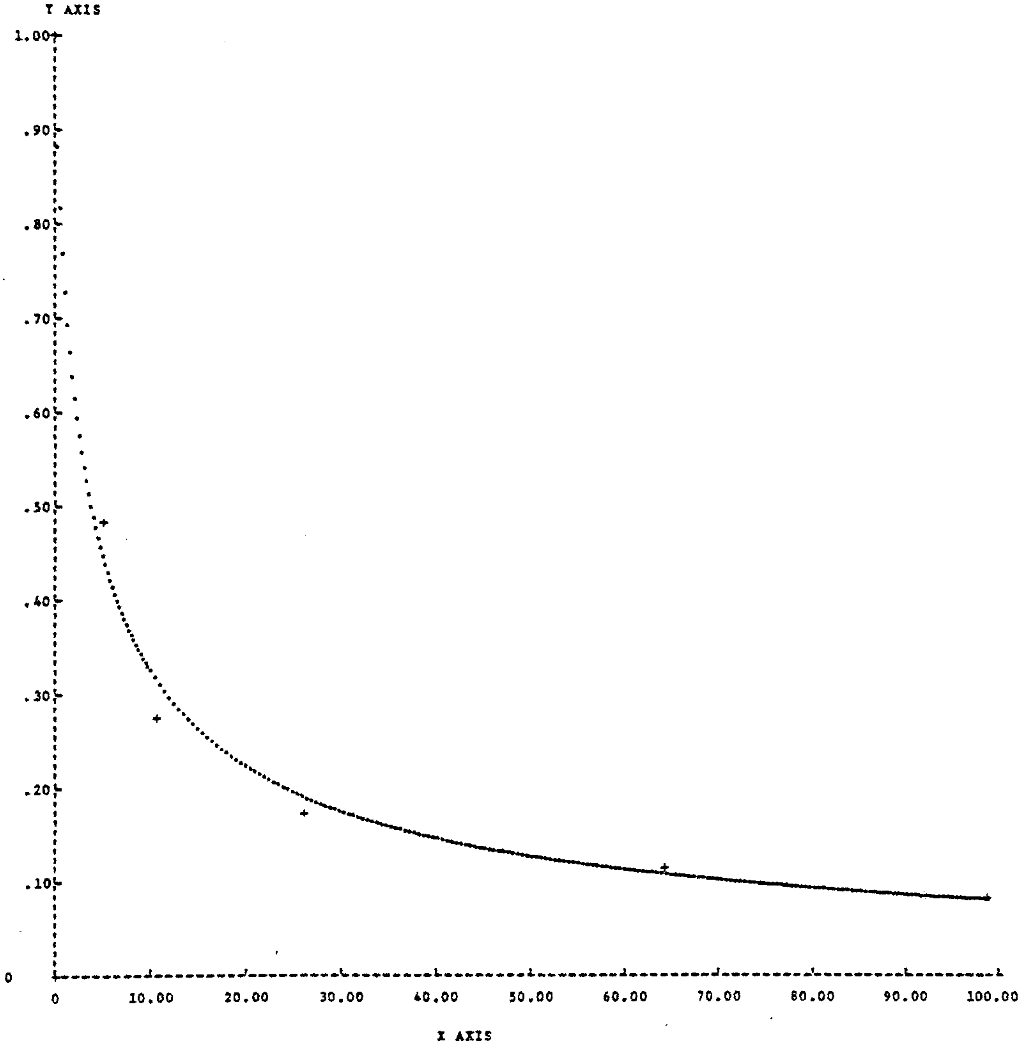

Figure A.1 SAR (x-axis) versus Relative Hydraulic Conductivity K_R (y-axis) for Anthony Sandy Loam at C_T = 12.5 meq/1 -- The curve is drawn using $y = (1 + cx^n)^{-1}$ with c and n empirical constants.

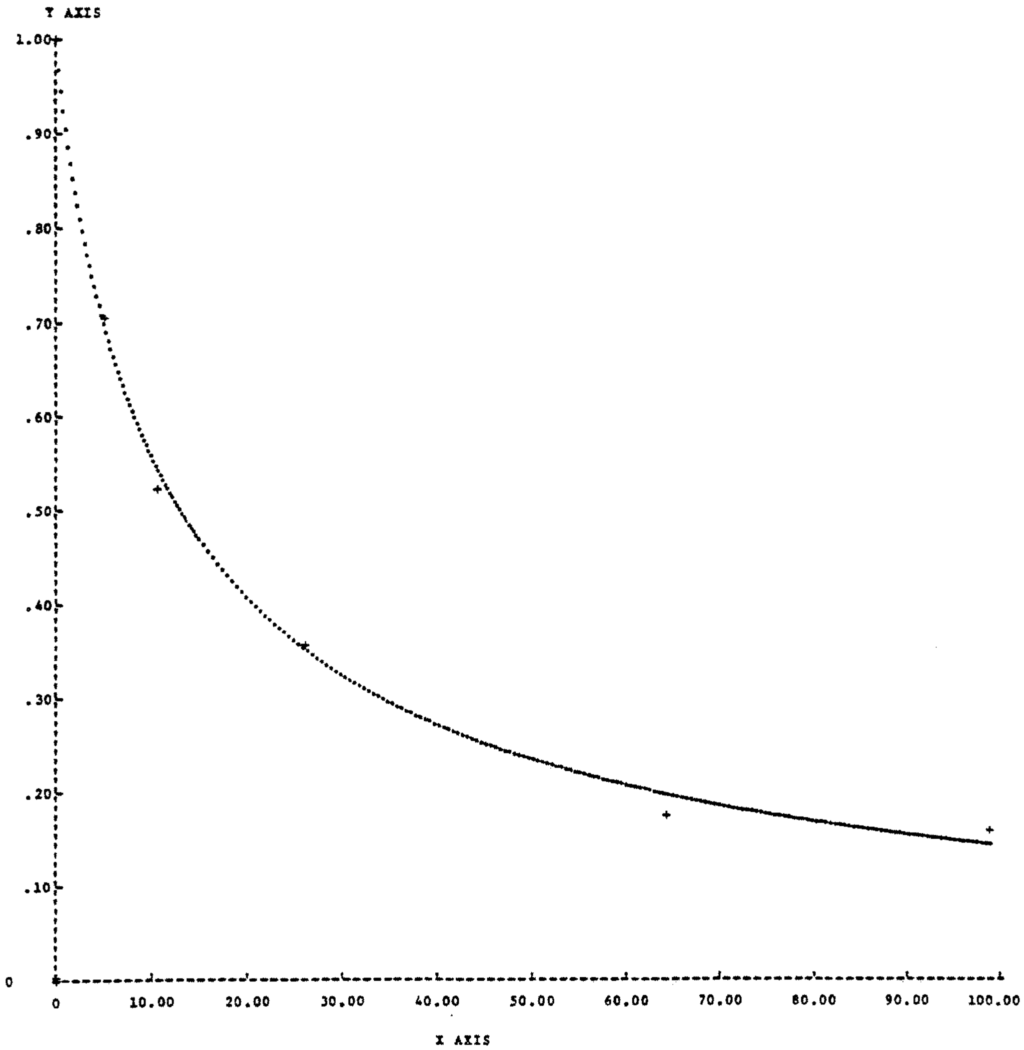

Figure A.2 SAR (x-axis) versus Relative Hydraulic Conductivity K_R (y-axis) for Grabe Loam at C_T = 12.5 meq/l. -- The curve is drawn using $y = (1 + cx^n)^{-1}$ with c and n empirical constants.

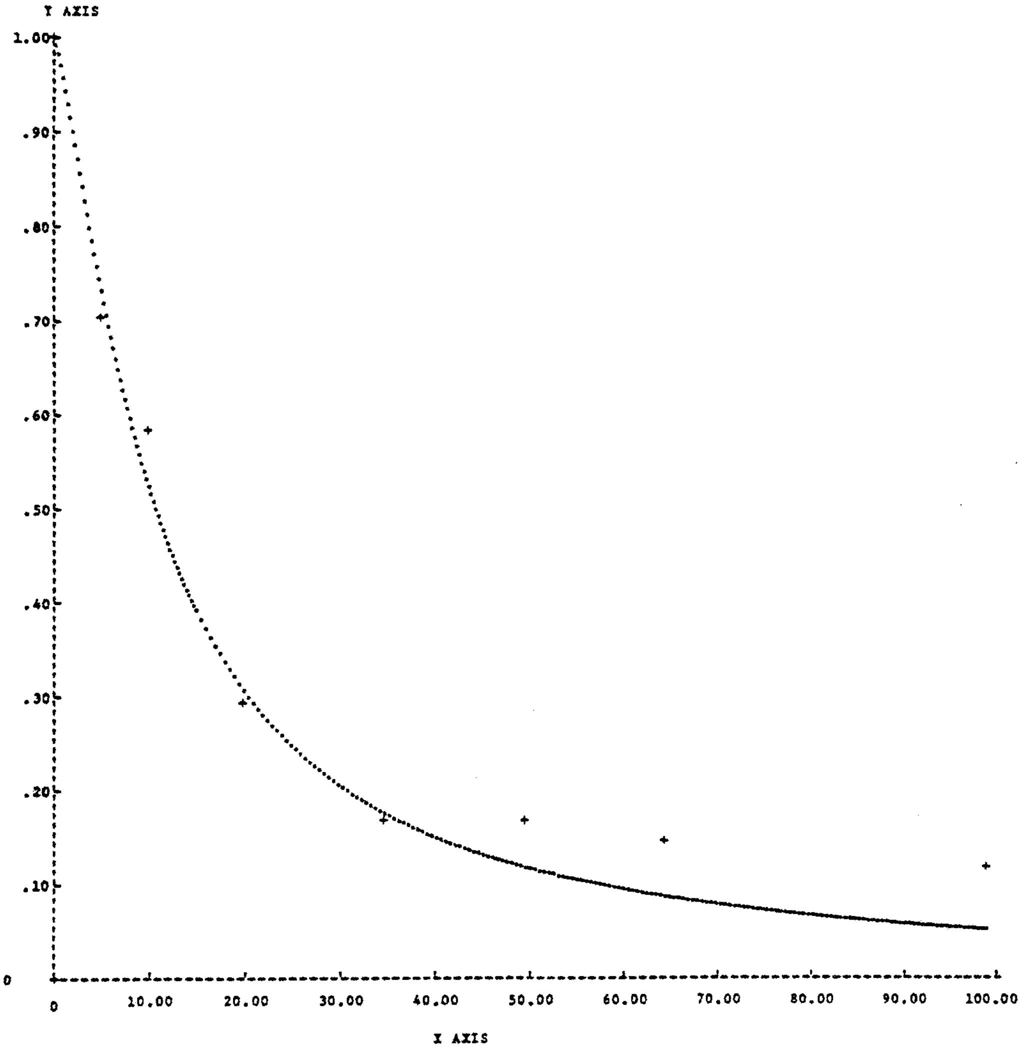

Figure A.3 SAR (x-axis) versus Relative Hydraulic Conductivity K_R (y-axis) for Mohave Clay Loam at C_T = 12.5 meq/l. -- The curve is drawn using $y = (1 + cx^n)^{-1}$ with c and empirical constants.

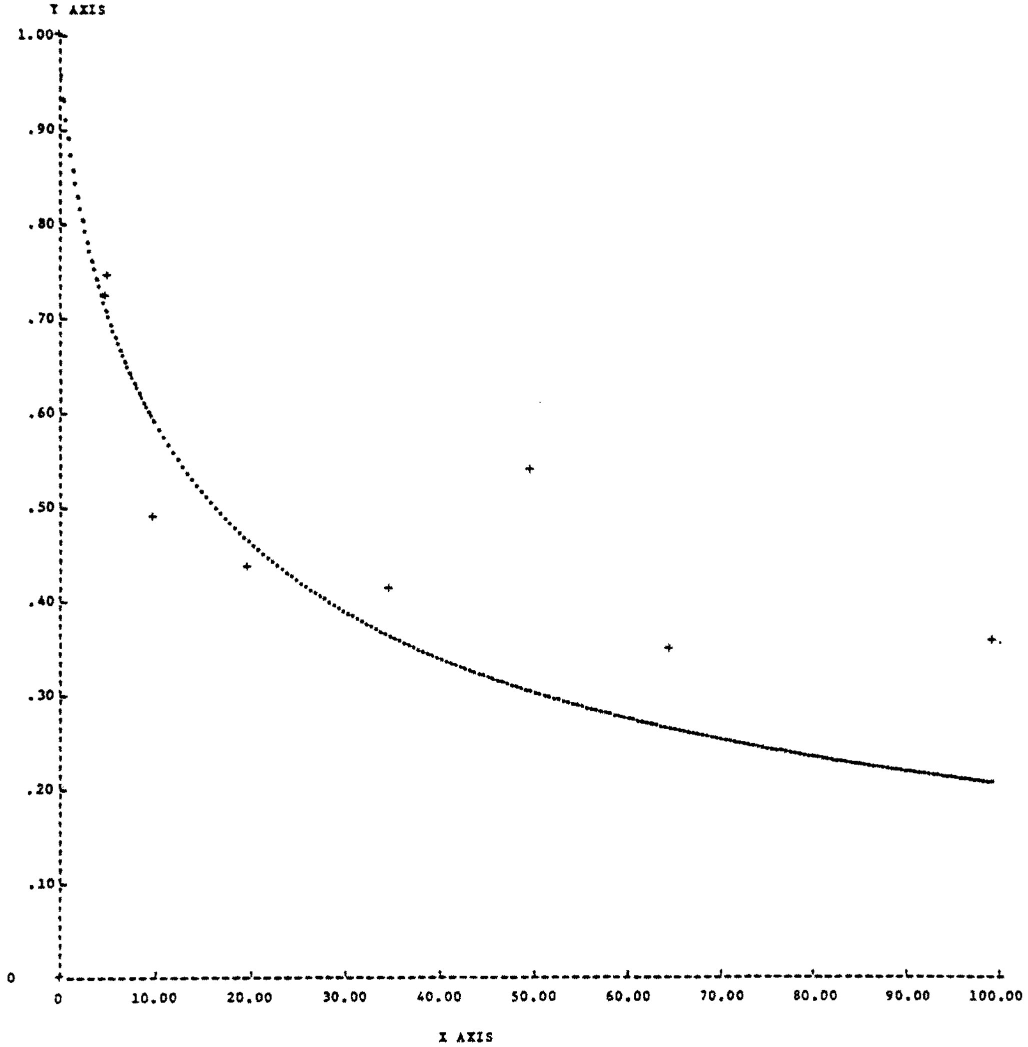

Figure A.4 SAR (x-axis) versus Relative Hydraulic Conductivity K_R (y-axis) for Pima Clay Loam at C_T = 12.5 meq/l. -- The curve is drawn using $y = (1 + cx^n)^{-1}$ with c and n empirical constants.

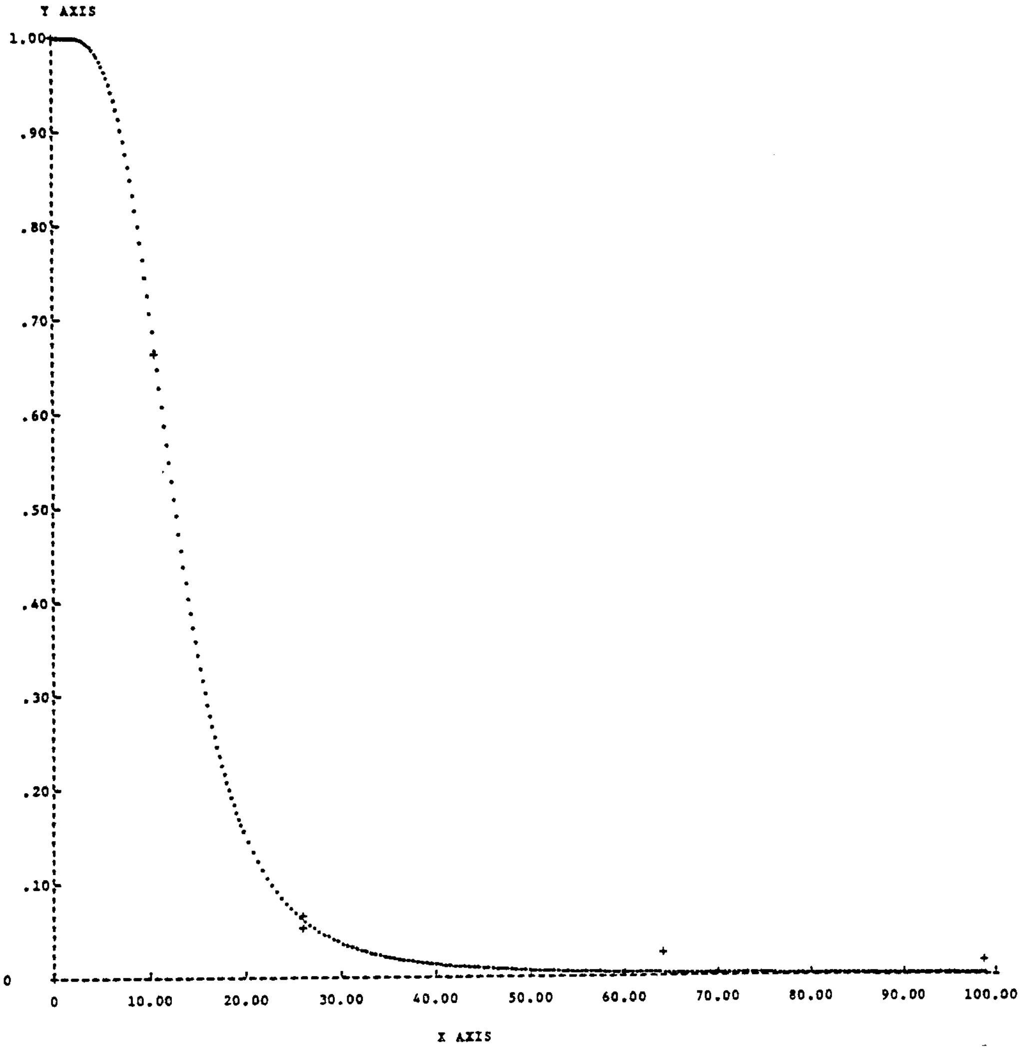

Figure A.5 SAR (x-axis) versus Relative Hydraulic Conductivity K_R (y-axis) for Vinton Loamy Sand at C_T = 12.5 meq/1. -- The curve is drawn using $y = (1 + cx^n)^{-1}$ with c and n empirical constants.

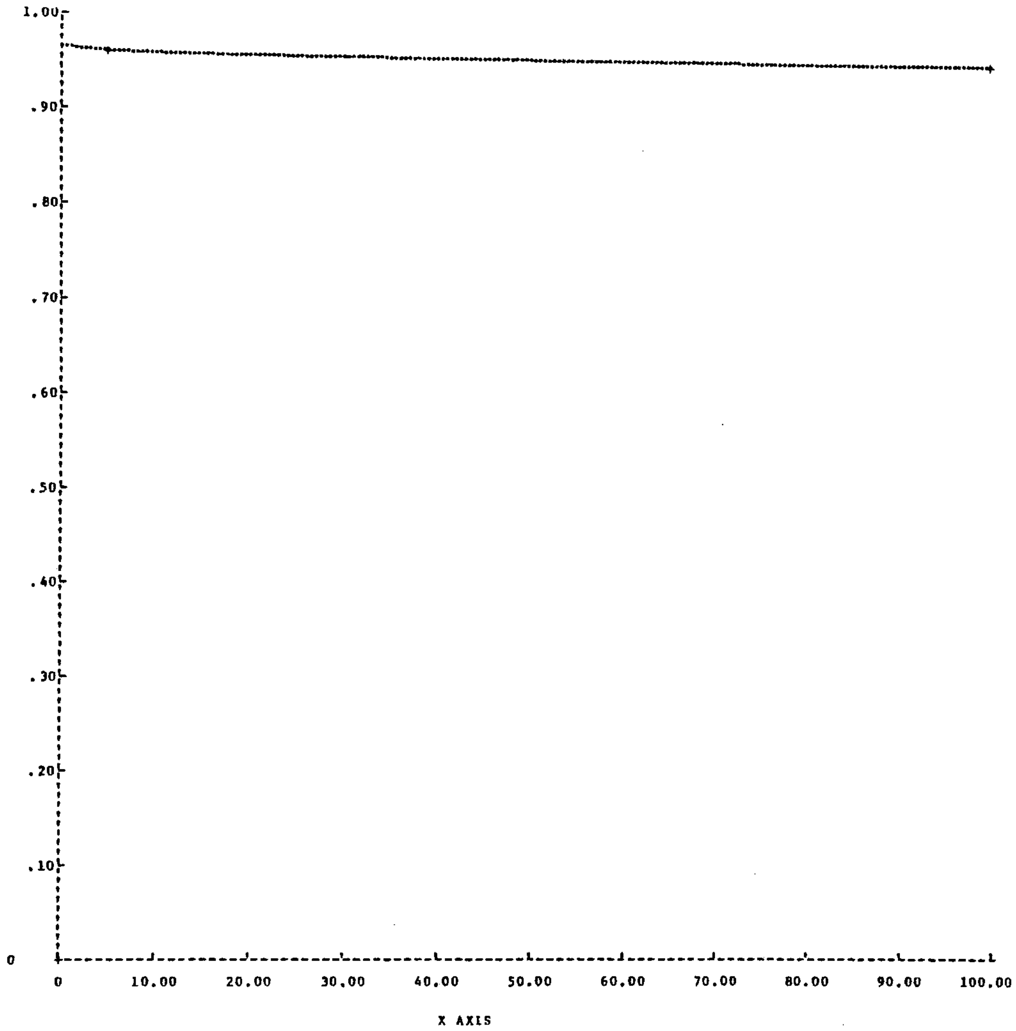

Figure A.6 SAR (x-axis) versus Relative Hydraulic Conductivity K_R (y-axis) for Aiken Clay Loam at C_T = 12.5 meq/l. -- The curve is drawn using $y = (1 + cx^n)^{-1}$ with c and n empirical constants. Data from McNeal (1965).

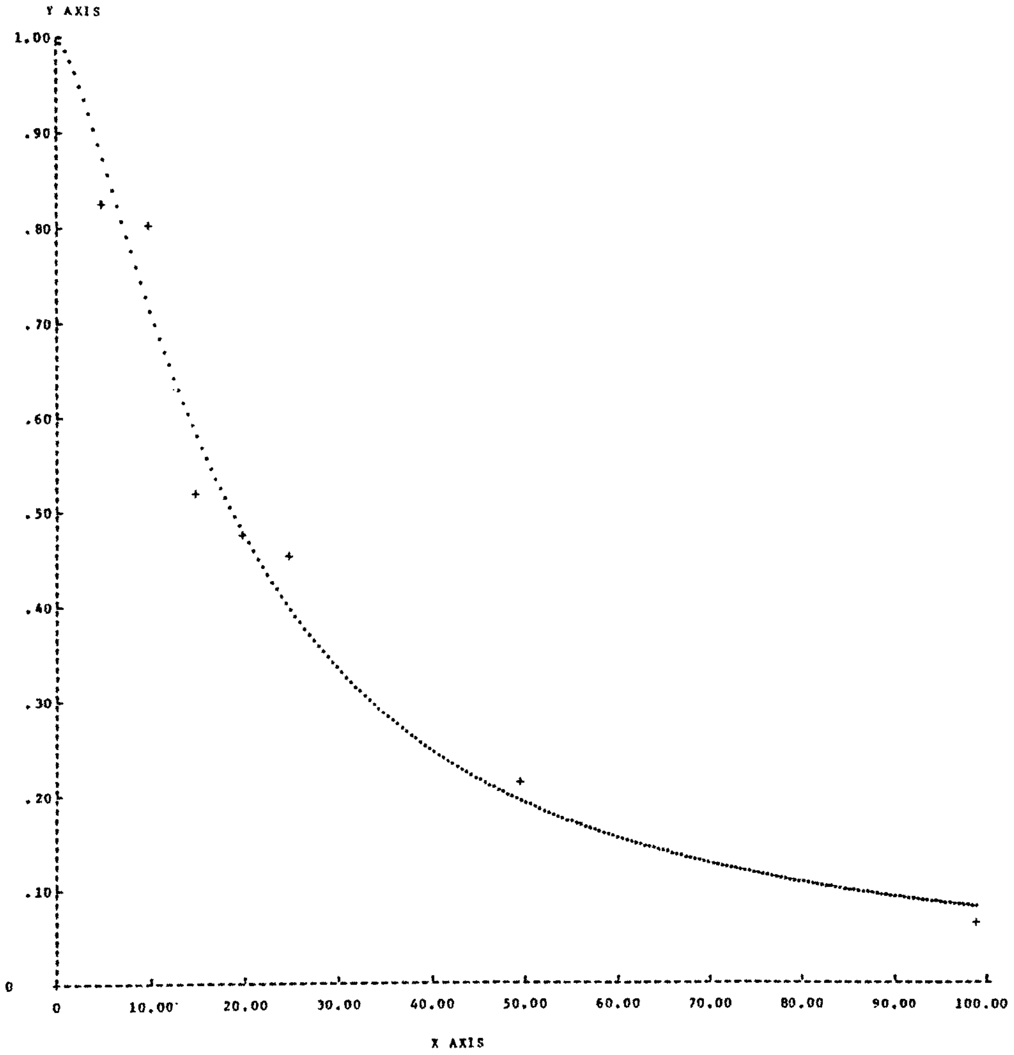

Figure A.7 SAR (x-axis) versus Relative Hydraulic Conductivity K_R (y-axis) for Gila Clay at $C_T = 12.5$ meq/1. -- The curve is drawn using $y = (1 + cx^n)^{-1}$ with c and empirical constants. Data from McNeal (1965).

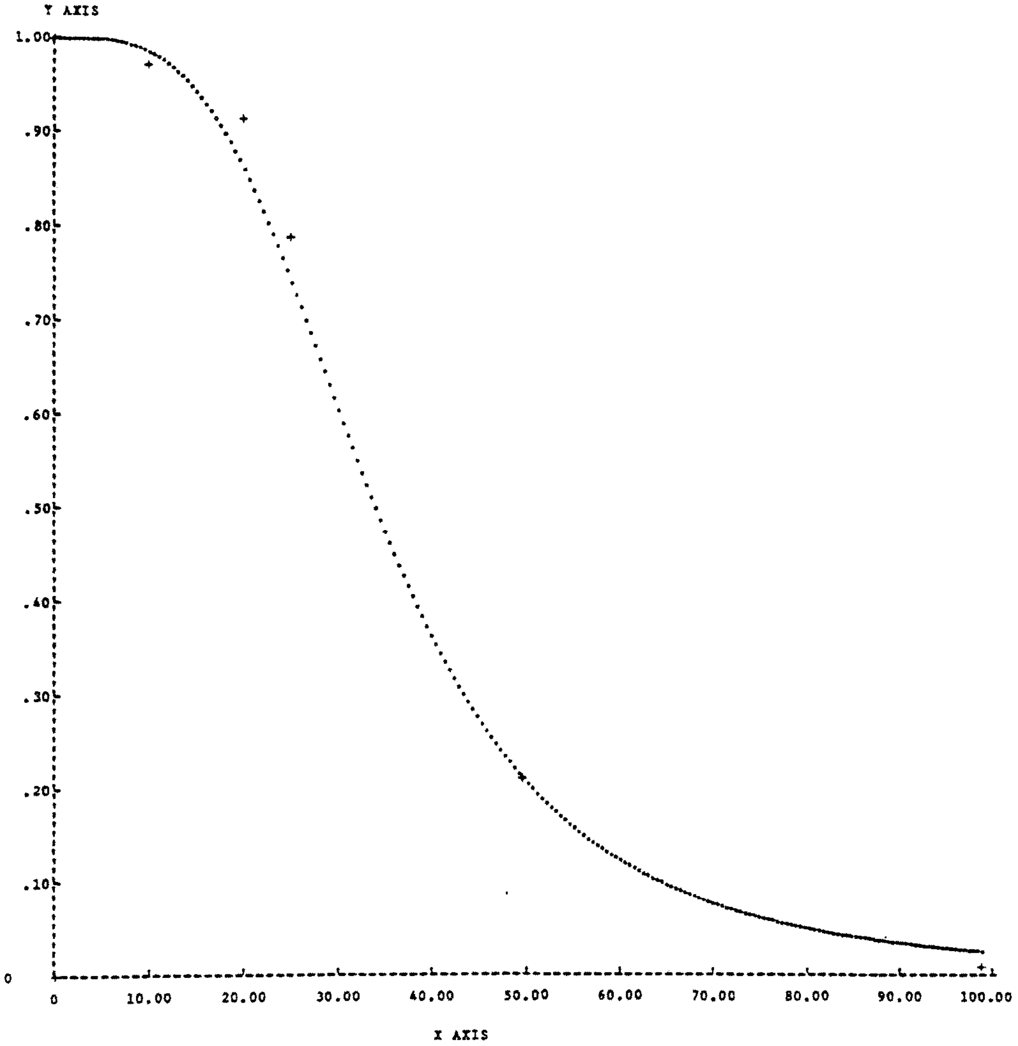

Figure A.8 SAR (x-axis) versus Relative Hydraulic Conductivity K_R (y-axis) for Grangeville Sandy Loam at C_T = 12.5 meq/l. -- The curve is drawn using $y = (1 + cx^n)^{-1}$ with c and n empirical constants. Data from McNeal (1965).

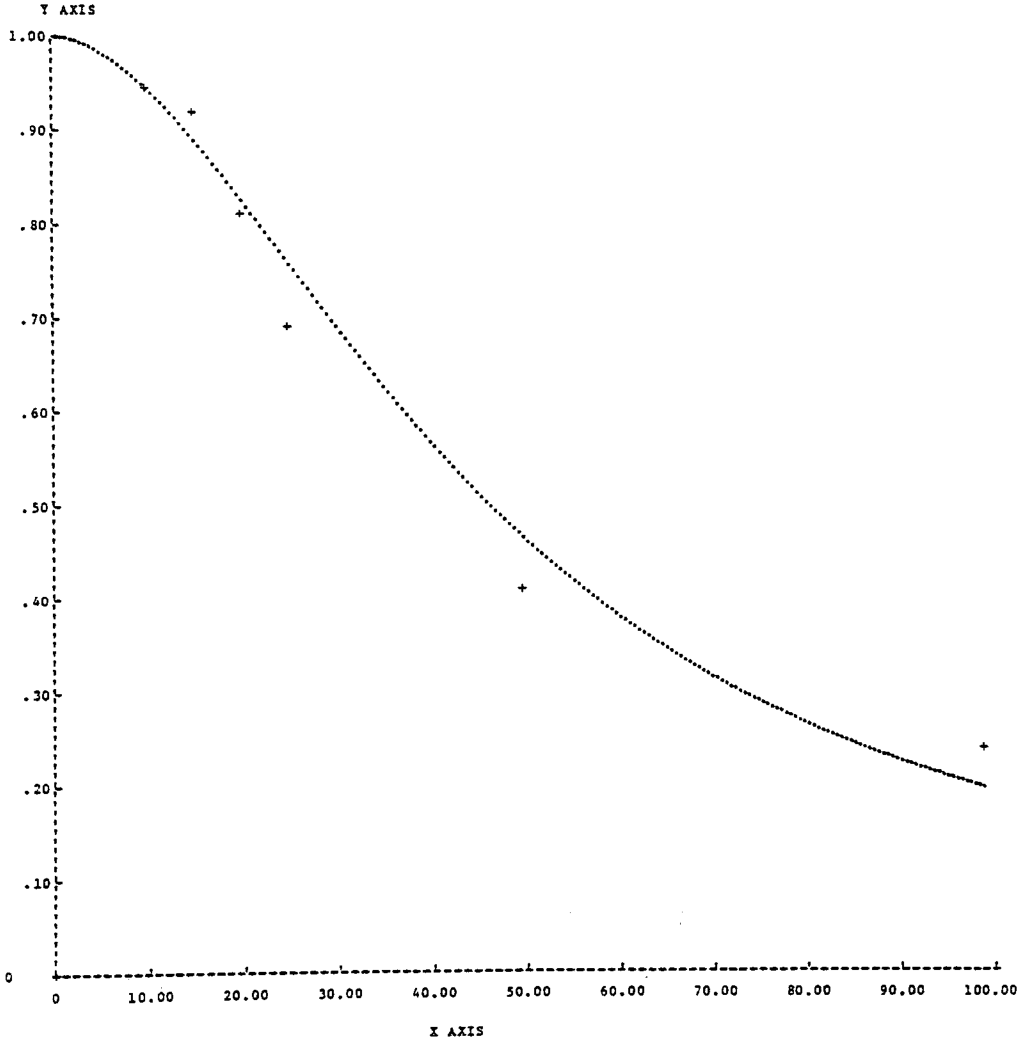

Figure A.9 SAR (x-axis) versus Relative Hydraulic Conductivity K_R (y-axis) for Oasis Clay Loam at $C_T = 12.5$ meq/1. -- The curve is drawn using $y = (1 + cx^n)^{-1}$ with c and n empirical constants. Data from McNeal (1965).

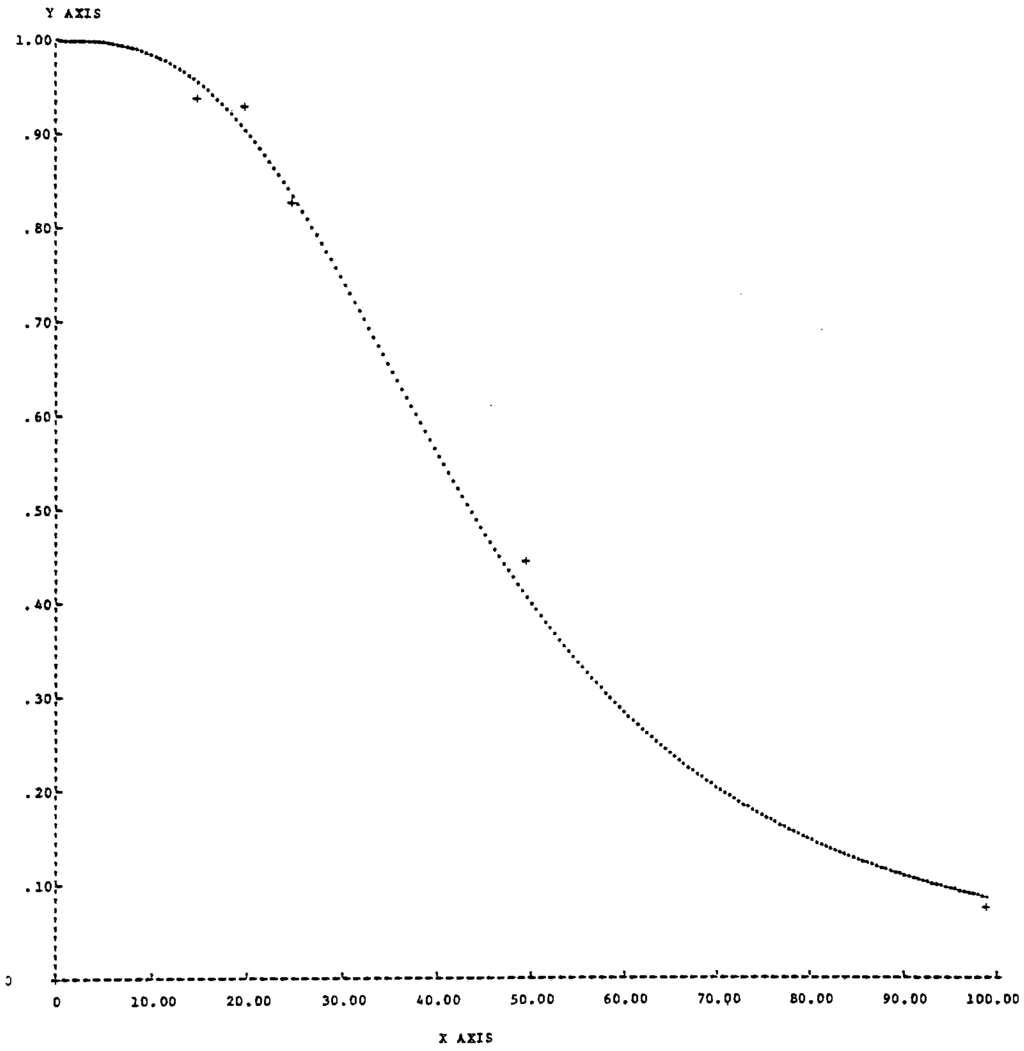

Figure A.10 SAR (x-axis) versus Relative Hydraulic Conductivity K_R (y-axis) for Pachappa Sandy Loam at C_T = 12.5 meq/l. -- The curve is drawn using $y = (1 + cx^n)^{-1}$ with c and n empirical constants. Data from McNeal (1965).

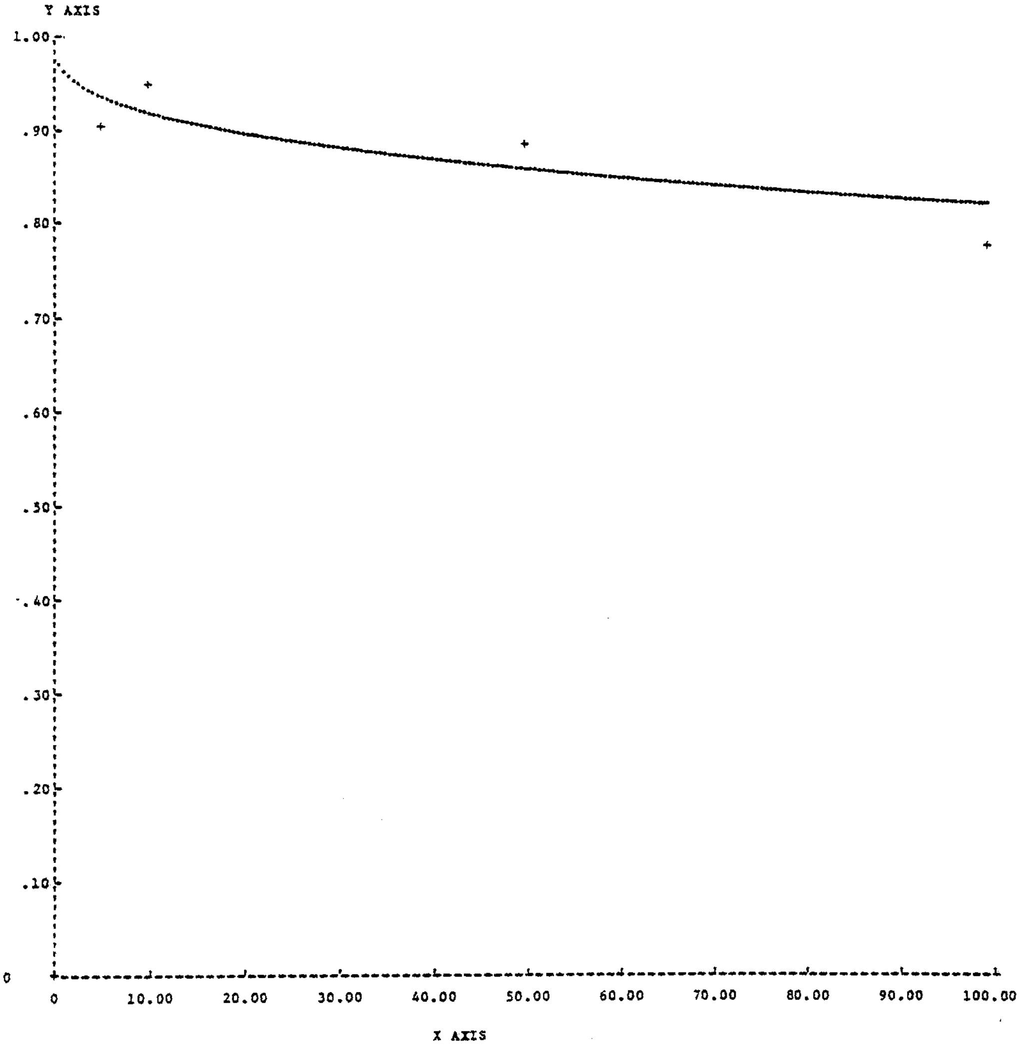

Figure A.11 SAR (x-axis) versus Relative Hydraulic Conductivity K_R (y-axis) for Vale Silt Loam at $C_T = 12.5$ meq/1. -- The curve is drawn using $y = (1 + cx^n)^{-1}$ with c and n empirical constants. Data from McNeal (1965).

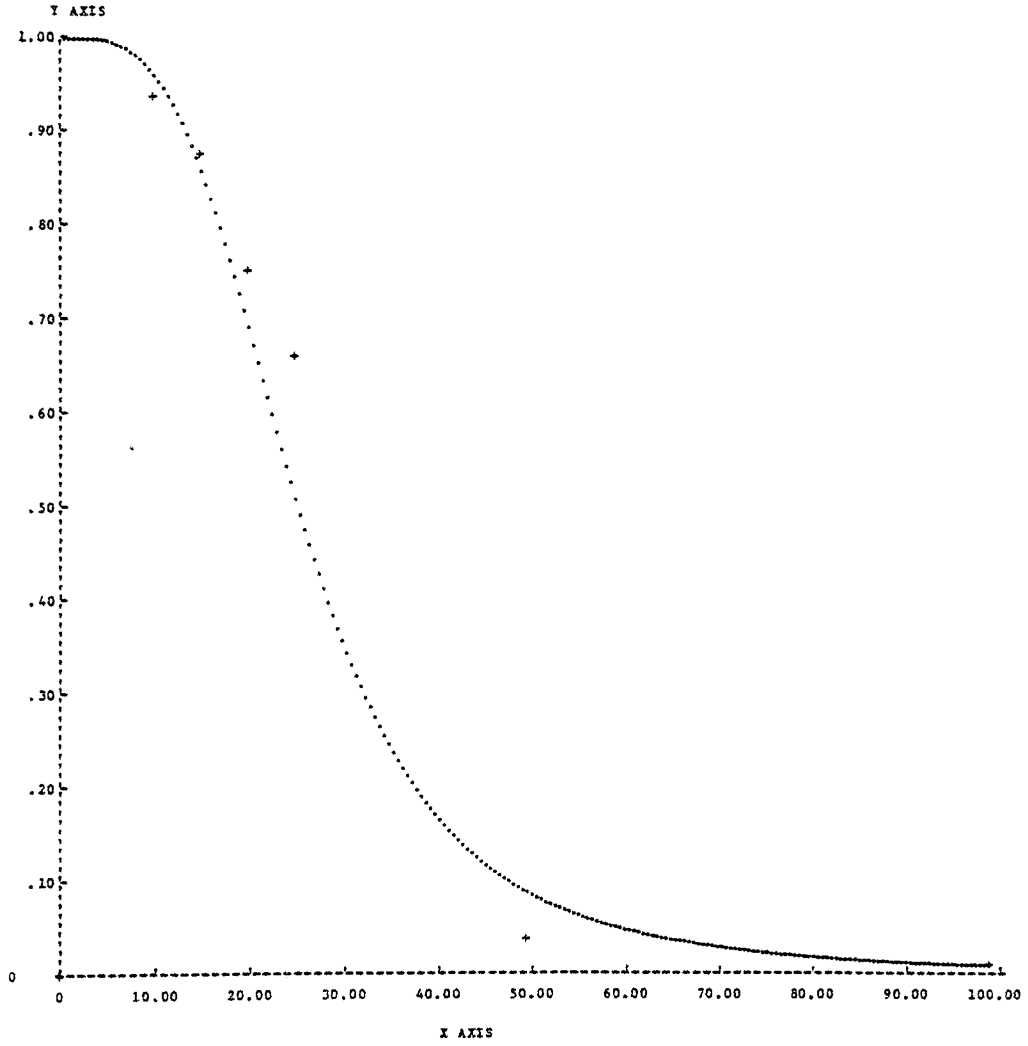

Figure A.12 SAR (x-axis) versus Relative Hydraulic Conductivity K_R (y-axis) for Waukena Clay Loam at C_T = 12.5 meq/l. -- The curve is drawn using $y = (1 + cx^n)^{-1}$ with c and n empirical constants. Data from McNeal (1965).

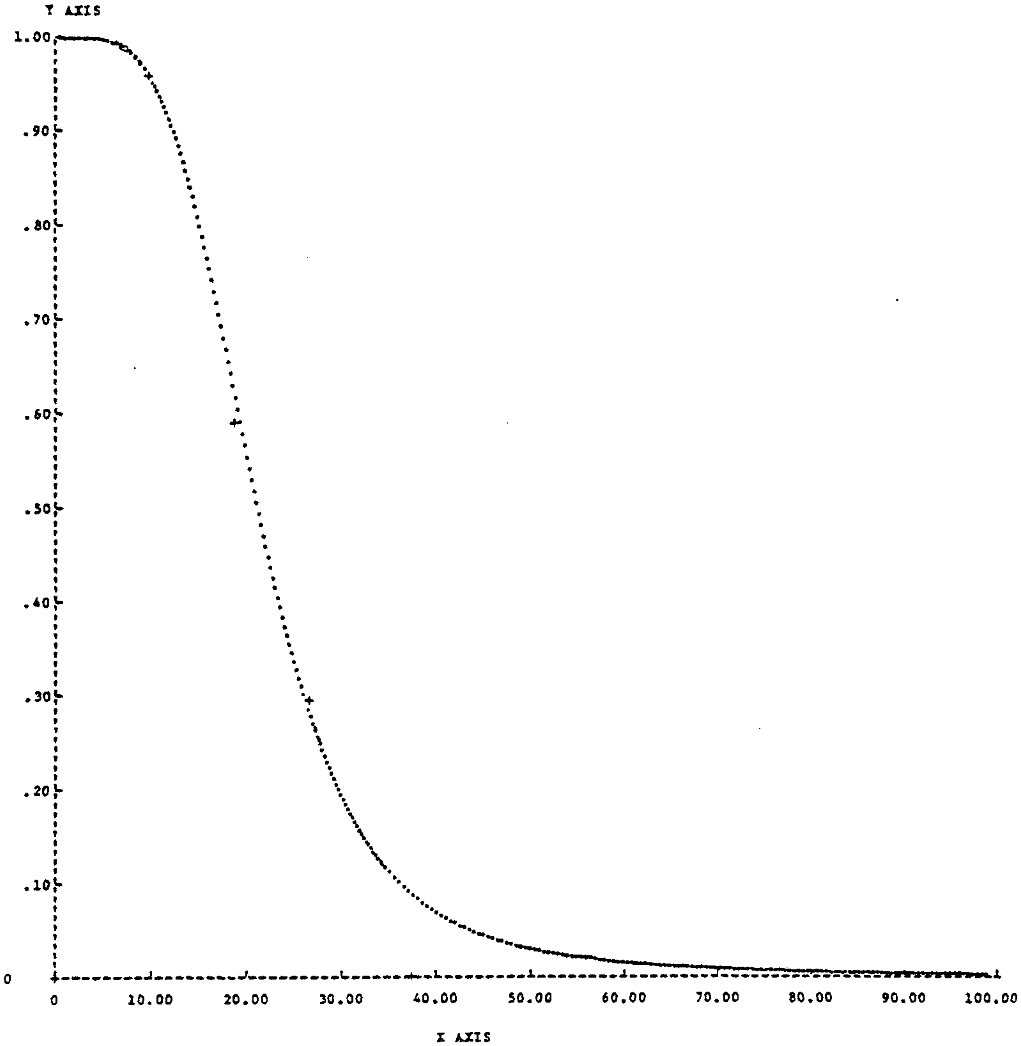

Figure A.13 SAR (x-axis) versus Relative Hydraulic Conductivity K_R (y-axis) for Beaumont Clay at C_T = 12.5 meq/l. -- The curve is drawn using $y = (1 + cx^n)^{-1}$ with c and n empirical constants. Data from Naghshineh-Pour (1968).

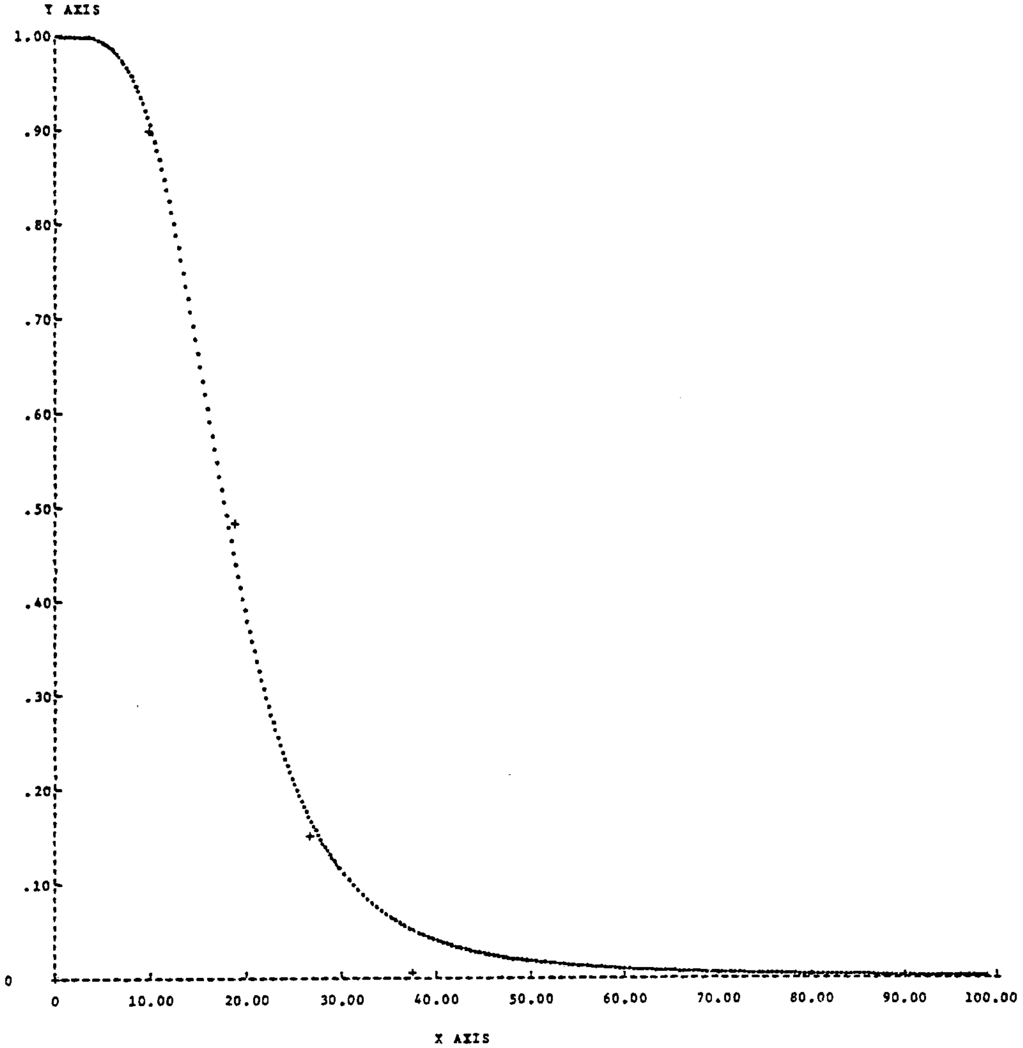

Figure A.14 SAR (x-axis) versus Relative Hydraulic Conductivity K_R (y-axis) for Houston Black Clay at C_T = 12.5 meq/1. -- The curve is drawn using $y = (1 + cx^n)^{-1}$ with c and n empirical constants. Data from Naghshineh-Pour (1968).

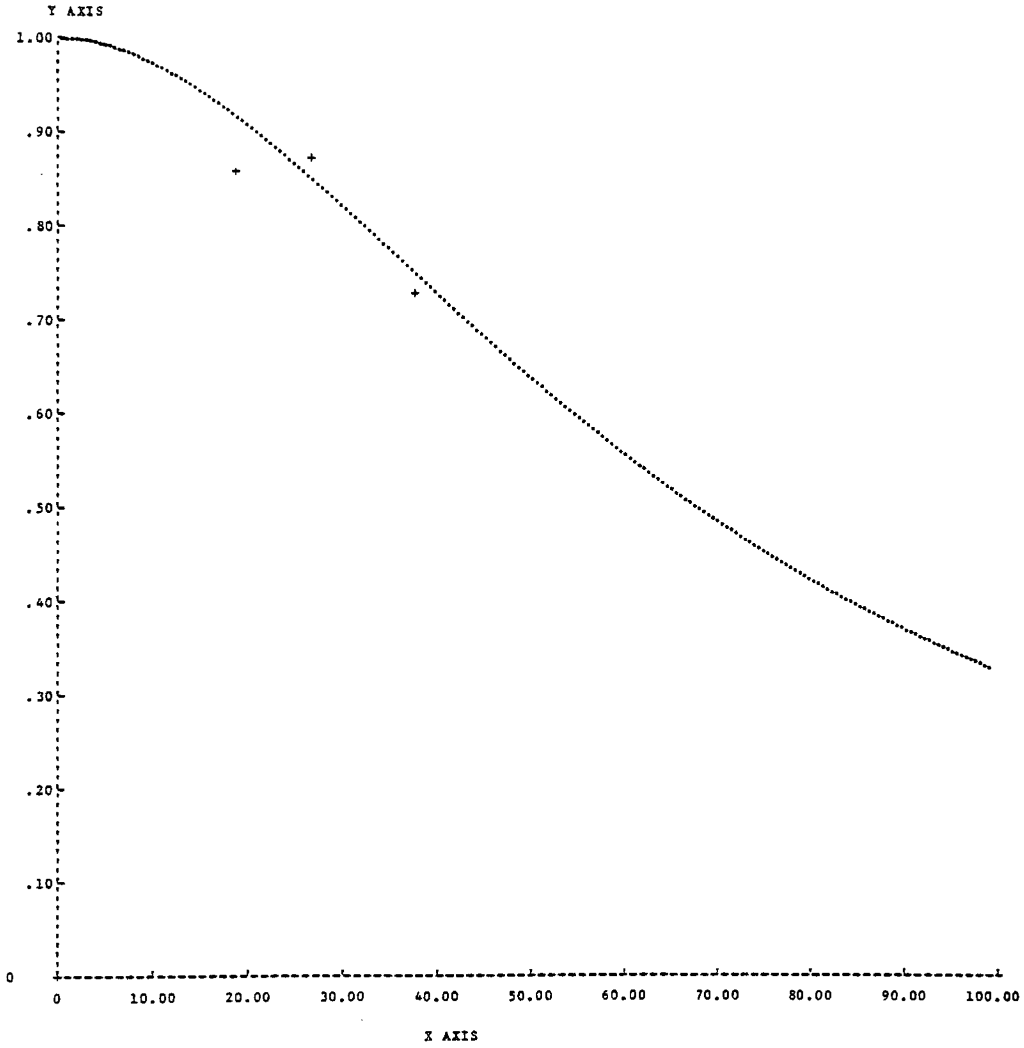

Figure A.15 SAR (x-axis) versus Relative Hydraulic Conductivity K_R (y-axis) for Katy Fine Sandy Loam at C_T = 12.5 meq/l. -- The curve is drawn using $y = (1 + cx^n)^{-1}$ with c and n empirical constants. Data from Naghshineh-Pour (1968).

Table A.1 Results of Hydraulic Conductivity Experiments Performed on Six Arizona Soils in This Study at a Total Solution Concentration of 12.5 meq/1.

	SAR[a]	Hydraulic Conductivity (cm/hr)	K_R[b]
Anthony soil	.0	6.23×10^{-2}	1.000
	5.2	3.01×10^{-2}	.483
	10.8	1.71×10^{-2}	.275
	26.4	1.09×10^{-2}	.174
	65.0	0.71×10^{-2}	.115
	100.0	0.51×10^{-2}	.083
	∞	0.58×10^{-2}	.093
Grabe soil	.0	2.56×10^{-2}	1.000
	5.2	1.80×10^{-2}	.706
	10.8	1.34×10^{-2}	.524
	26.4	0.92×10^{-2}	.359
	65.0	0.45×10^{-2}	.177
	100.0	0.41×10^{-2}	.161
	∞	0.69×10^{-2}	.272
Mohave soil	.0	1.50×10^{-2}	1.000
	5.0	1.05×10^{-2}	.704
	10.0	0.87×10^{-2}	.584
	20.0	0.44×10^{-2}	.295
	35.0	0.25×10^{-2}	.169
	50.0	0.25×10^{-2}	.169
	65.0	0.22×10^{-2}	.147
	100.0	0.17×10^{-2}	.119
	∞	0.21×10^{-2}	.140
Pima soil	.0	9.9×10^{-3}	1.000
	5.0	7.1×10^{-3}	.723
	5.2	7.4×10^{-3}	.744
	10.0	4.8×10^{-3}	.489
	20.0	4.3×10^{-3}	.436
	35.0	4.1×10^{-3}	.414
	50.0	5.3×10^{-3}	.542
	65.0	3.4×10^{-3}	.351
	100.0	3.5×10^{-3}	.361
	∞	2.6×10^{-3}	.265

Table A.1, Continued.

	SAR[a]	Hydraulic Conductivity (cm/hr)	K_R[b]
Vinton soil	.0	69.53×10^{-2}	1.000
	5.2	94.19×10^{-2}	1.354
	10.8	46.24×10^{-2}	.665
	26.4	4.65×10^{-2}	.066
	26.4	3.70×10^{-2}	.053
	65.0	1.79×10^{-2}	.025
	100.0	1.16×10^{-2}	.016
	∞	1.98×10^{-2}	.021
Whitehouse soil	.0	2.3×10^{-4}	1.000
	5.0	2.2×10^{-4}	.954
	10.0	2.1×10^{-4}	.909
	20.0	2.1×10^{-4}	.909
	35.0	2.5×10^{-4}	1.090
	50.0	0.7×10^{-4}	.318
	65.0	2.0×10^{-4}	.863
	100.0	2.1×10^{-4}	.909
	∞	2.3×10^{-4}	1.000

[a] SAR of the input solution.

[b] K_R is the hydraulic conductivity relative to the value given at SAR = 0.

Table A.2 Results of Hydraulic Conductivity Experiments Performed at a Total Solution Concentration of 12.5 meq/l by McNeal (1965).

	SAR[a]	Hydraulic Conductivity (cm/hr)	K_R[b]
Aiken soil	.0	1.28	1.000
	5.0	1.23	.960
	10.0	1.25	.976
	15.0	1.25	.976
	20.0	1.32	1.031
	25.0	1.25	.976
	50.0	1.30	1.015
	100.0	1.22	.953
	∞	1.28	1.000
Gila soil	.0	4.6×10^{-2}	1.000
	5.0	3.8×10^{-2}	.826
	10.0	3.7×10^{-2}	.804
	15.0	2.4×10^{-2}	.521
	20.0	2.2×10^{-2}	.478
	25.0	2.1×10^{-2}	.456
	50.0	1.0×10^{-2}	.217
	100.0	$.3 \times 10^{-2}$	.065
	∞	$.3 \times 10^{-2}$	.065
Grangeville soil	.0	5.36	1.000
	5.0	5.69	1.061
	10.0	5.22	.973
	15.0	5.52	1.029
	20.0	4.91	.916
	25.0	4.24	.791
	50.0	1.15	.214
	100.0	.10	.019
	∞	.00	.000
Oasis soil	.0	7.5×10^{-2}	1.000
	5.0	7.7×10^{-2}	1.026
	10.0	7.1×10^{-2}	.946
	15.0	6.9×10^{-2}	.920
	20.0	6.1×10^{-2}	.813
	25.0	5.2×10^{-2}	.693
	50.0	3.1×10^{-2}	.413
	100.0	1.8×10^{-2}	.240
	∞	0.5×10^{-2}	.066

Table A.2, Continued.

	SAR[a]	Hydraulic Conductivity (cm/hr)	K_R[b]
Pachappa soil	.0	1.18	1.000
	5.0	1.24	1.050
	10.0	1.21	1.025
	15.0	1.11	.940
	20.0	1.10	.932
	25.0	.98	.830
	50.0	.53	.449
	100.0	.09	.076
	∞	.01	.008
Vale soil	.0	$2.00\text{x}10^{-1}$	1.000
	5.0	$1.81\text{x}10^{-1}$	.905
	10.0	$1.90\text{x}10^{-1}$	.950
	15.0	$1.97\text{x}10^{-1}$	.985
	20.0	$1.98\text{x}10^{-1}$	.990
	25.0	$1.95\text{x}10^{-1}$	.975
	50.0	$1.78\text{x}10^{-1}$	.890
	100.0	$1.57\text{x}10^{-1}$	.785
	∞	$1.21\text{x}10^{-1}$	.605
Waukena soil	.0	$1.79\text{x}10^{-1}$	1.000
	5.0	$1.91\text{x}10^{-1}$	1.067
	10.0	$1.68\text{x}10^{-1}$	.938
	15.0	$1.57\text{x}10^{-1}$	.877
	20.0	$1.35\text{x}10^{-1}$	.754
	25.0	$1.19\text{x}10^{-1}$	.664
	50.0	$0.07\text{x}10^{-1}$	.039
	100.0	$0.02\text{x}10^{-1}$	.011
	∞	--	--

[a] SAR of the input solution.

[b] K_R is the hydraulic conductivity relative to the value given at SAR = 0.

Table A.3 Results of Hydraulic Conductivity Experiments Performed at a Total Solution Concentration of 10.5 meq/l by Naghshineh-Pour (1968).

	SAR[a]	Hydraulic Conductivity (cm/hr)	K_R[b]
Beaumont soil	.0	6.78	1.000
	10.0	6.50	.958
	19.0	4.02	.592
	27.0	2.00	.294
	38.0	8×10^{-3}	.001
Houston soil	.0	13.21	1.000
	10.0	11.90	.900
	19.0	6.42	.485
	27.0	2.01	.152
	38.0	.08	.006
Katy soil	.0	3.85	1.000
	10.0	4.27	1.109
	19.0	3.50	.909
	27.0	3.37	.875
	38.0	2.82	.732
Nacogdoches soil	.0	6.15	1.000
	10.0	6.54	1.063
	19.0	5.29	.860
	27.0	5.82	.946
	38.0	7.82	1.271

[a] SAR of the input solution.

[b] K_R is the hydraulic conductivity relative to the value given at SAR = 0.

APPENDIX B

CORRELATIONS OF THE UNTRANSFORMED SOIL PROPERTIES

Soil property abbreviations used are: ρ_B, packed bulk density (gm/cm^3); pH, pH of saturated soil paste; CEC, cation exchange capacity (meq/100 g); ESP, exchangeable sodium percentage (fraction); EC_e, electrical conductivity of the saturation extract at 25°C (mmho/cm); organics, fraction of organic material in soil; $CaCO_3$, fraction calcium carbonate in soil; sand, silt, and clay values are fractional.

Bulk density and electrical conductivity were not available for Naghshineh-Pour (1968) soils. Significant values of the correlation coefficient (r) were obtained from Table A.13 (Steel and Torrie, 1960).

Table B.1 5 Soils (Boyer).

	ρ_B	Sand	Silt	Clay	pH	CEC	ESP	EC_e	Organics
ρ_B	--								
Sand	.84	--							
Silt	-.90*	-.97**							
Clay	-.61	-.92*	.80	--					
pH	.54	.48	-.51	-.36	--				
CEC	-.89*	-.94*	.92*	.85	-.69	--			
ESP	-.78	-.74	.84	.48	-.10	.59	--		
EC_e	-.81	-.73	.86	.40	-.56	.70	.85	--	
Organics	-.86	-.88*	.95*	.64	-.60	.84	.84	.96**	--
$CaCO_3$	-.94*	-.89*	.96**	.64	-.62	.89*	.83	.94*	.98**

*Value of $|r|$ significant at 5% = 0.878.

**Value of $|r|$ significant at 1% = 0.959.

Table B.2 7 Soils (McNeal, 1965).

	ρ_B	Sand	Silt	Clay	pH	CEC	ESP	EC_e	Organics
ρ_B	--								
Sand	.36	--							
Silt	.23	-.56	--						
Clay	-.63	-.47	-.47	--					
pH	-.34	-.07	.46	-.41	--				
CEC	-.91**	-.46	.13	.38	.03	--			
ESP	-.08	-.35	.67	-.34	.76*	.41	--		
EC_e	.33	-.52	.82*	-.31	.33	.01	.62	--	
Organics	-.02	-.58	-.04	.66	-.76*	-.16	-.41	.03	--
$CaCO_3$	.39	-.44	.48	-.04	-.02	-.20	.22	.87**	.25

*Value of $|r|$ significant at 5% = 0.754.

**Value of $|r|$ significant at 1% = 0.874.

Table B.3 8 Soils (Boyer; Naghshineh-Pour, 1968).

	ρ_B	Sand	Silt	Clay	pH	CEC	ESP	EC_e	Organics
ρ_B	--								
Sand	--	--							
Silt	--	-.84**	--						
Clay	--	-.94**	.60	--					
pH	--	.50	-.16	-.64	--				
CEC	--	-.90**	.64	.91**	-.34	--			
ESP	--	.19	.19	-.40	.13	-.53	--		
EC_e	--	--	--	--	--	--	--	--	
Organics	--	-.82**	.67	.85**	-.36	.95**	-.52	--	--
$CaCO_3$	--	-.55	.47	.50	.28	.76*	-.36	--	.65

*Value of $|r|$ significant at 5% = .707.

**Value of $|r|$ significant at 1% = .834.

Table B.4 10 Soils (McNeal, 1965; Naghshineh-Pour, 1968).

	ρ_B	Sand	Silt	Clay	pH	CEC	ESP	EC_e	Organics
ρ_B	--								
Sand	--	--							
Silt	--	-.47	--						
Clay	--	-.59	-.44	--					
pH	--	.04	.50	-.50	--				
CEC	--	-.64*	.08	.58	.19	--			
ESP	--	-.13	.67*	-.48	.70*	.02	--		
EC_e	--	--	--	--	--	--	--	--	
Organics	--	-.73*	.00	.74*	-.52	.43	-.46	--	--
$CaCO_3$	--	-.49	.29	.23	.16	.43	-.03	--	.45

*Value of |r| significant at 5% = 0.632.

**Value of |r| significant at 1% = 0.765.

Table B.5 12 Soils (McNeal, 1965; Boyer).

	ρ_B	Sand	Silt	Clay	pH	CEC	ESP	EC_e	Organics
ρ_B	--								
Sand	.76**	--							
Silt	-.48	-.77**	--						
Clay	-.64**	-.65*	.02	--					
pH	-.14	-.04	.34	-.34	--				
CEC	-.80**	-.69*	.45	.55	.50	--			
ESP	-.40	-.46	.68*	-.08	.70	.51	--		
EC_e	-.23	-.53	.76**	-.07	.31	.20	.68*		
Organics	-.34	-.62*	.24	.69*	-.70	.11	-.20	.15	
$CaCO_3$	-.04	-.44	.52	.06	-.03	-.01	.25	.82**	.32

*Value of $|r|$ significant at 5% = 0.576.

**Value of $|r|$ significant at 1% = 0.708.

Table B.6 15 Soils (Boyer; McNeal, 1965; Naghshineh-Pour, 1968).

	ρ_B	Sand	Silt	Clay	pH	CEC	ESP	EC_e	Organics
ρ_B	--								
Sand	--	--							
Silt	--	-.69**	--						
Clay	-	-.73**	.02	--					
pH	--	.15	.30	-.50	--				
CEC	--	-.75**	.35	.70**	.06	--			
ESP	--	-.28	.65**	-.22	.61*	.16	--		
EC_e	--	--	--	--	--	--	--	--	
Organics	--	-.71**	.24	.77**	-.54*	.55*	-.29	--	--
$CaCO_3$	--	-.46	.36	.30	.11	.47	.03	--	.50

*Value of $|r|$ significant at 5% = 0.514.

**Value of $|r|$ significant at 1% = 0.641.

APPENDIX C

CORRELATIONS OF THE UNTRANSFORMED SOIL PROPERTIES FOR SOILS CONTAINING CALCIUM CARBONATE

Soil property abbreviations used are: ρ_B, packed bulk density (g/cm^3); pH, pH of saturated soil paste; CEC, cation exchange capacity (meq/100 g); ESP, exchangeable sodium percentage (fraction); EC_e, electrical conductivity of the saturation extract at 25°C (mmho/cm); organics, soil organic material (fraction); $CaCO_3$, soil calcium carbonate (fraction); sand, silt, and clay values are fractional.

The five soils of the current study all contain $CaCO_3$ and correlations are found in Tables B.1-B.6.

Bulk density and electrical conductivity were not available for Naghshineh-Pour (1968) soils. Significant values of the correlation coefficient (r) were obtained from Table A.13 (Steel and Torrie, 1960).

Table C.1 6 Soils Containing $CaCO_3$ (McNeal, 1965).

	ρ_B	Sand	Silt	Clay	pH	CEC	ESP	EC_e	Organics
ρ_B	--								
Sand	.38	--							
Silt	.24	-.62	--						
Clay	-.72	-.43	-.44	--					
pH	-.45	-.36	.51	-.17	--				
CEC	-.93**	-.55	.09	.52	.69	--			
ESP	-.07	-.46	.66	-.23	.81	.35	--		
EC_e	.36	-.62	.81**	-.22	.18	-.07	.58	--	
Organics	-.10	-.68	.16	.60	-.43	.06	-.23	.42	--
$CaCO_3$	.42	-.51	.46	.06	-.32	-.27	.15	.86*	.71

*Value of $|r|$ significant at 5% = 0.811.

**Value of $|r|$ significant at 1% = 0.917.

Table C.2 11 Soils Containing $CaCO_3$ (Boyer; McNeal, 1965).

	ρ_B	Sand	Silt	Clay	pH	CEC	ESP	EC_e	Organics
ρ_B	--								
Sand	.75**	--							
Silt	-.49	-.80**	--						
Clay	-.62*	-.62*	.03	--					
pH	-.42	-.36	.49	-.04	--				
CEC	-.83**	-.74**	.45	.65*	.65*	--			
ESP	-.46	-.56	.69*	.02	.82**	.51	--		
EC_e	-.27	-.60*	.77**	.00	.29	.19	.67*	--	
Organics	-.30	-.66*	.38	.61*	-.33	.26	-.07	.42	--
$CaCO_3$	-.08	-.52	.53	.17	-.24	-.03	.22	.81**	.74**

*Value of $|r|$ significant at 5% = 0.602.

**Value of $|r|$ significant at 1% = 0.735.

Table C.3 12 Soils Containing $CaCO_3$ (Boyer; McNeal, 1965; Naghshineh-Pour, 1968).

	ρ_B	Sand	Silt	Clay	pH	CEC	ESP	EC_e	Organics
ρ_B	--								
Sand	--	--							
Silt	--	-.75**	--						
Clay	--	-.69*	.05	--					
pH	--	-.26	.47	-.12	--				
CEC	-	-.77**	.35	.78**	.34	--			
ESP	--	-.41	.66*	-.11	.82**	.21	--		
EC_e	--	--	--	--	--	--	--	--	
Organics	--	-.70*	.28	.76**	-.34	.65*	-.21	--	--
$CaCO_3$	--	-.61*	.35	.54	-.28	.54	-.04	--	.90**

*Value of $|r|$ significant at 5% = 0.576.

**Value of $|r|$ significant at 1% = 0.708.

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