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Investigation of Seepage Reduction by Soil-Water Chemical Reactions in Irrigation Canals

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A Thesis for the Degree
of Master of Science in
Civil Engineering

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INVESTIGATION OF SEEPAGE REDUCTION BY SOIL-WATER CHEMICAL REACTIONS IN IRRIGATION CANALS

A Thesis
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ABSTRACT

A procedure for estimating potential changes in the hydraulic conductivity of a silt layer in a canal was developed following McNeal's method for predicting the hydraulic conductivity of soils in the presence of mixed-salt solutions. The reason for using this method was to analyze the effect on seepage from the canal.

A series of experiments on soil columns was conducted in order to determine the surface sealing effect by fine sediments and metabolic products of micro-organisms activity. Similar tests were conducted using sterile soil and water. A comparison of predicted and measured conductivities was made.

Physical dispersion is perhaps the primary factor in causing changes in seepage rate with time. For the case studied, the reduction in conductivity that could be attributed to soil-water chemical reaction is minor in magnitude as is also the effect of microbial action. Silting effect due to settlement of soil particles carried in canal water appears to have only a minor effect on conductivity change also.

PEDRO A. HERNANDEZ

The author was born in Havana, Cuba, on August 6, 1937. He attended the Central Methodist School for six years and the Instituto de Segunda Enseñanza No. 1 for five years, both in Havana. In October, 1954, he entered the University of Havana majoring in Civil Engineering. In 1956 his studies were interrupted due to political problems which originated the closing of the University. Meanwhile he attended the Vocational High School of the Institute de Segunda Enseñanza No. 2 and obtained the certificate of Land Surveyor in June, 1958, and worked temporarily in that field. He continued his university education after the University was opened in August 1959 and graduated in April, 1963, with a Bachelor of Science degree in Civil Engineering. In May, 1962, he had started to work in the Hydraulic Department of the College of Civil Engineering as an Instructor, being named Assistant Professor in January, 1966. He was in charge of the Hydrology Section of the Hydraulic Department and collaborated with the Hydrology Department of the National Water Resources Institute in different hydrologic studies. In December, 1968, he was named a member of the Cuban National Committee for the IHD.

In October, 1969, he received a scholarship from the Netherlands Government in order to attend the International Courses in Hydraulic and Sanitary Engineering at Delft. He graduated in September, 1970, with a Diploma in Hydrological Engineering. After 5 months in Spain, he came to the United States and entered the University of Idaho (February, 1971) for the continuance of his advanced study.

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SUMMARY

The McNeal's method for predicting the hydraulic conductivity of soils in the presence of a wide range of mixed-salt solutions is outlined and its equation was applied to three different soil layers, A, B, and C, of a Portneuf silt-loam soil. The application of this method was simply a tool for predicting the hydraulic conductivity.

The experiments carried out to obtain the relationship between the relative hydraulic conductivities and ESP, for three different salt concentrations of the ambient solution, revealed irrigations with a salt concentration of about 1 meq/liter decreases the relative hydraulic conductivity to 0.35, 0.73 and 0.86 in the A, B, and C, layers, respectively. Irrigation with the common ditch water produces only a slight reduction in layer A; none is expected in layers B and C.

A series of experiments on soil columns was conducted to determine the surface sealing effect of fine sediments and metabolic products or micro-organism activity. The results of the runs using both unsterile and sterile soil and water, as well as the removal of an approximately 4mm thick top layer of each unsterile soil column, leads to the conclusion that neither microbial activities nor silting effect are responsible for the reductions in hydraulic conductivity.

Physical dispersion is probably the main factor in causing changes in seepage rate with time.

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CHAPTER I

INTRODUCTION

Seepage losses from irrigation canals constitute an exceedingly serious problem in the United States, mainly in the West, and in other parts of the world as well. Conveyance losses from irrigation canals can constitute a large percentage of water diverted. Robinson and Rohwer (26) have found that of the water diverted for irrigation in the seventeen western states of the United States, nearly 35,000,000 acre ft. per year, or approximately 40%, is lost before it reaches the farms. This loss consists of seepage, evaporation, transpiration by aquatic weeds, waste, and leakage. The greatest amount of water is lost by seepage.

Water lost by seepage is not only lost to the canal to which it is appropriated, but may also result in considerable damage to lower lands by constributing to high water-table conditions which reduce crop production and value of land for various other uses. Although the water is lost to the canal, the loss may still be beneficial. A considerable amount of the seepage water may contribute to ground water supplies or reappear as return flow increasing stream flow.

The expanding world population is placing an increasing demand on agricultural production of food and fiber. Much of this increased demand may be met through reclamation of existing unproductive lands and better utilization of certain marginal lands. Future development therefore requires increased water supplies.

In planning efficient water management, whether it be the removal of excess water by drainage (either rainwater or irrigation water) or the utilization and replenishment of deeper aquifers for water supply, the need of estimating future effects of proposed management practices requires continued effort toward finding solutions. The solution of such problems requires sound information on the permeability of soils.

The Problem

Field observations and the reports of other experimenters indicate that the seepage rate decreases throughout the season in many operating irrigation canals.

This reduction in seepage rate is related to the change in hydraulic conductivity of the soil profile or to changes in the conductivity of the top layer of the profile.

This decrease in conductivity may be attributed to natural sealing processes associated with:

a) the sealing of surface by fine sediments,
b) the effects of the chemical properties of soils and waters on the physical properties of soils, and
c) the effect of microorganism activity.

Preliminary work by Brockway and Worstell (4) concluded that considerable study was necessary on the effects of solution composition on the hydraulic conductivity of the silt layer in canals in the southern Idaho area. In addition, it was suggested that a study of the influence on hydraulic conductivity due to microbiological activity be undertaken.

Objectives

The purpose of this research was to develop a better understanding of the factors influencing changes in hydraulic conductivity of submerged soils under conditions such as those occurring in operating irrigation canals.

The main objectives of the study are:

1. To determine whether naturally occurring seepage reduction exists due to the decrease of hydraulic conductivity resulting from clay swelling in place or clay dispersion and movement into pores as affected by the chemical properties of soil and water.
2. To predict in each case the conductivity reduction using measurable soil and water parameters. Laboratory measurements of permeability may give unreliable estimates and although _in situ_ techniques are most reliable, considerable time, effort and a lot of money are necessary for their performance.
3. To gain insight as to the nature of the reduced permeability caused by the possible dispersion of aggregates due to microbial attack and to the clogging of pores by products produced by microbial activity.

CHAPTER II

REVIEW OF LITERATURE

To systematically tie together the subjects of seepage and permeability as affected by electrolyte concentration and microbial activity, the literature will be reviewed in the following order: Field studies; flow through porous media; hydraulic conductivity related to swelling of soil; and effects of micro-organisms on permeability.

Field Studies and Observations

Conveyance Losses

According to Israelsen (13), water conveyance efficiency is the ratio of the volume of water delivered to farms to the volume that is taken in at the head gate of the canal.

A large portion of the water diverted into irrigation canals is lost in transit or conveyance. This loss, as stated before, is composed of five parts:

1. Leakage
2. Waste
3. Transpiration
4. Evaporation
5. Seepage

Leakage is defined as the water lost through poorly maintained gates and structures. Regulatory waste represents the amount which is lost through automatic wasteways or merely discharged into wasteways. Although the waste and leakage may be very high in some instances, they can be reduced by better management, therefore, these losses will not be discussed in this thesis.

The rate of evaporation from irrigation canals has been measured in several instances with the floating-type pan, and in nearly all cases the quantity is negligible; hence, this source of loss is ignored in this discussion. The same may be said relative to transpiration losses.

Seepage

According to Tolman (29) seepage is the movement of water into or out of the ground. A similar definition is given by Meinzer (21), but for movement he substitutes percolation which Tolman uses only in the restricted sense of movement of water in saturated media. Seepage in the context of this thesis refers to the process of water movement into and through the soil from a body of surface water as may occur in canals, streams or impoundments.

Field Studies

In 1948, the University of Idaho, Engineering Experiment Station, in cooperation with the Bureau of Reclamation, initiated a special research program for the study of seepage control and measurement under the direction of Warnick (32).

Recently, Brockway and Worstell (4) have published a report on canal seepage studies where they evaluate seepage losses in a section of the Northside Pumping Canal. In this project average seepage rates from 86 seepage meter tests (with the ARS meter) are compared with ponding rates. Field tensiometer studies and an investigation of an impeding layer on the canal bottom were also reported.

Flow of Water Through Porous Media

The rate of movement of water through soil is of considerable importance in many aspects of agricultural and urban life. The entry of water into soil, the movement of water to plant roots, the flow of water to drains and wells, and the evaporation of water from the surface of soil are but a few of the obvious situations in which the rate of movement plays an important role. An important soil property involved in the behavior of soil water flow systems is the conductivity of the soil to transmit water. Measurements of conductivity of saturated soil have long been made. The data are of use in analysis of any saturated soil water-flow system. These include drainage of soils for agricultural as well as engineering purposes. Drainage of highways, airports, and construction sites, and seepage below dams are among the latter.

Darcy's Law for Saturated Media

The accepted concept that in saturated porous media the rate of steady flow of a fluid through the media ia proportional to the pressure gradient in the direction of flow was proposed by Darch in 1856. He confined his experiments to the case of vertical flow through saturated beds of sands. The law which he enunciated for this case has subsequently been generalized, the most generalized forms, however, still being known as Darcy's law. The rate of fluid flow is generally recognized to be inversely proportional to the dynamic viscosity of the fluid. Expressed mathematically for one-dimensional flow, Darcy's law may be extended to the following equation:

$$u = \frac{K'}{\mu} \cdot \frac{d(P+\gamma Z)}{dL} = K \frac{d\left(\frac{P}{\gamma} + Z\right)}{dL} = Ki \tag{1}$$

in which:

u is the volume flux in the direction of flow. L/T.

K' is a coefficient called permeability or "intrinsic permeability". It is a function of the geometry of the medium. L^2.

μ is dynamic viscosity. FT/L^2.

K is a coefficient called hydraulic conductivity. It is a function of the fluid viscosity as well as of the geometry of the medium. L/T.

P is pressure, which can be above or below atmospheric. F/L^2.

γ is the specific weight of the fluid or weight per unit volume of fluid. F/L^3.

i is the hydraulic gradient, $d(P/\gamma+Z)/dL$. Dimensionless.

Z is the elevation of a point in a porous medium above a datum. L.

L is the length or distance between two points in a porous medium in the direction of flow. L.

Darcy's Law for Unsaturated Media

In a completely saturated porous media all the pore space is more or less effective in conducting water. By implication the hydrostatic pressure (P/γ) is everywhere positive, and such circumstances commonly attend the engineering problems.

If the soil is unsaturated, the total effective cross-sectional area available for the flow is reduced by the pore space filled with air. Unsaturation implies that the soil experiences suction everywhere, so that the "potential" difference between the opposite faces of the sample must be maintained not by different heads of positive hydrostatic pressure but by different imposed suctions.

The difficulty is, of course, that since in general the suction will vary along the axis of the sample, so also will the moisture content and the hydraulic conductivity. The steady velocity of flow being the same everywhere, it follows from equation (1) that the hydraulic gradient varies along the axis of the sample.

The flux of water at a certain point in an unsaturated soil may be considered to be given by the product of the conductivity at that point and the driving force which is expressed as the hydraulic gradient. That is:

$$u = K(\theta) \cdot i \tag{2}$$

Equation (2) is an extension of Darcy's law to unsaturated soil. In general, the functional relationship, $K = f(\theta)$, is not a single-valued but is affected by hysteresis. The value of K will be different if a given value of θ is obtained by starting with a dry medium and increasing the liquid saturation than if the same value of θ is obtained by removing liquid from an initially vacuum-saturated medium (see Figure 1).

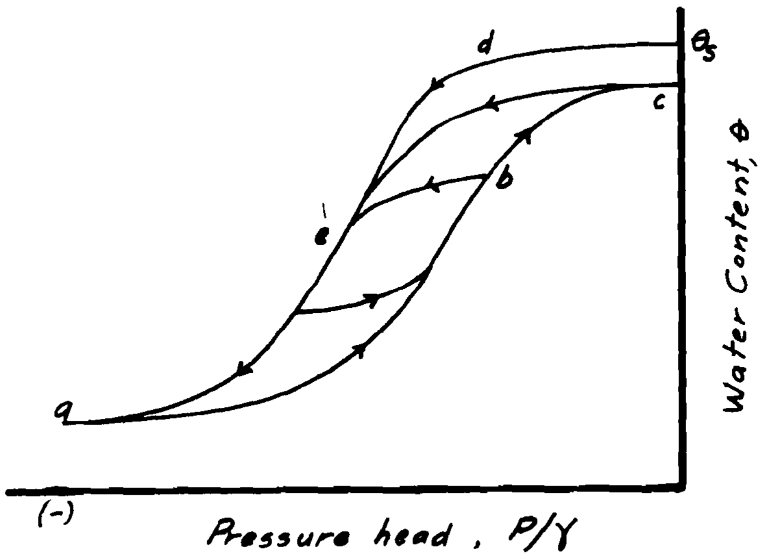

Figure 1. Illustration of hysteresis in the water content versus pressure head relation for a relatively coarse material in stable packing.

Richards (25) was the first one who developed the theory that Darcy's law holds in a general form for flow in unsaturated media. Later Childs and Collis-George (7) and others confirmed the theory by experimentation.

Irrigation and drainage engineers are faced with the problem of getting water into or out of soil. In either case, the flow phenomena involved is flow through partially saturated porous media. In the design of drainage and irrigation systems, as well as in the majority studies of hydraulic conductivities, engineers have made the simplifying assumptions that soil is either completely saturated with water or it is completely unsaturated and that resistance to flow of air is negligible. Such assumptions are in most cases far from realistic.

Brooks and Corey (6) have developed a theory for isotropic media which describe the functional relationships among the saturation, the pressure difference between air and water, and the permeabilities of air and water as well as the properties of porous media which affect them. These functional relationships can be described in terms of two soil parameters: One called the "bubbling pressure" and the other called the "pore-size distribution index".

It is necessary to point out, however, in this case a comparison of the saturated conductivity measured in the laboratory with field estimates (Brockway and Worstell, 1967), in which the moisture flow beneath the layer is unsaturated, are valid since the moisture content of the layer in the field is probably very near saturation. In other words, the "bubbling pressure" is close to zero and the conductivity of the layer does not vary appreciably.

That is the reason it is possible to proceed in this thesis on the assumption that the Darcy equation (Eq. 1) is valid and a good approximation of the field case which is being studied through laboratory tests.

Factors Affecting Seepage

Interpretation of the results of tests of seepage from a canal requires a knowledge of the factors affecting it. Principal among these are the following.

a) initial intrinsic permeability of the soils of the canal bed,
b) depth of water in the canal,
c) wetted perimeter of the canal,
d) depth to the groundwater table,
e) the rate of deposition of sediment on the canal bed,
f) chemistry of the soil and seeping water,
g) biological factors.

Since all these factors may act simultaneously, and some of them tend to counteract each other, it is difficult to segregate the effect of any one of them. Because of the many variables involved and the complexity of their relations, no satisfactory formula for computing seepage utilizing all the variables has ever been developed. It is necessary to add that the permeability of the soil of the canal bed is dependent also on the percent of entrained air in the soil, temperature of the seeping water and the barometric pressure.

The factor most important in determining rate of seepage is the permeability of the material forming the bed of the canal. According to Richards (25), permeability is the quality or state of a porous medium relating to the readiness with which such a medium conducts or transmits fluids under standard conditions. This definition encompasses both the properties of the fluid and the porous media. When water is the only fluid considered, hydraulic conductivity can be used to designate permeability. Viscosity and density are the fluid properties affecting hydraulic conductivity. With an increase in temperature, both viscosity and density decrease. Hydraulic conductivity increases with a decrease in viscosity and decreases with a decrease in density as seen in the equation:

$$K = \frac{\gamma K'}{\mu} = \frac{\rho g K'}{\mu} = \frac{g K'}{\nu} \qquad (3)$$

in which:

K is hydraulic conductivity. L/T.

γ is the specific weight of the fluid. F/L^3.

ρ is the mass density of the fluid. FT^2/L^4.

g is the gravitational acceleration constant. L/T^2.

μ is dynamic viscosity. FT/L^2.

K' is intrinsic permeability or simply a coefficient called permeability. L^2.

ν is kinematic viscosity. L^2/T.

When referring to the water carrying properties of the porous media itself, intrinsic permeability is the designation which should be used. It is influenced both by pore size and by percentage of pore space, or porosity. As pore size decreases, permeability decreases in approximately the same ratio as the square of pore diameter Tolman (29), resulting in relative imperviousness of clays, which have high porosity but very small pore diameter.

Seepage rates from canals can change with time because of changes that occur in bed material. Water moving into the soil carries small particles in suspension and deposits them in pore spaces, which gradually reduces the porosity of the soil. If the water contains a considerable amount of clay or silt, the process may markedly reduce the seepage rate in a relatively short time. This is not always true as reported by Shen (28) in his study of sediment-sealing with bentonite in a dune sand. The surface sealing is vulnerable to puncturing by animals and plants, cracking by drying or freezing, or removal by water or wind erosion. In addition to the problems of a surface coating, many of the canals have unstable sections. Waves and flowing water cut the banks. Animals work the soil of the canal section and sand dunes move along the canal bottom.

Seepage rate is a function of the head available to drive the water through the soil. This factor depends not only on the depth of water in the canal but also on the depth to the ground water table. If the ground water level is above the water surface in the canal, water will seep into the canal from the surrounding area. If it is below the bottom of the canal, the effective head depends on the depth of water in the canal and the length of soil column required to use up the available head. For intermediate ground water levels, the effective head is equal to the difference in level between the water table and the water surface in the canal. The greater the wetted area the greater the total seepage.

Air entrapped in the soil voids, as reported by Christiansen (8), has a definite effect on intrinsic permeability. He concluded that air is entrapped as bubbles in the soil when naturally wetted. The gradual absorption of the entrained air into the water in the soil matrix increases soil porosity and temporarily increases the seepage rate.

The relationship between seepage rate and barometric pressure is not well defined but there are investigations which show that a direct relationship might exist. Rise in barometric pressure, theoretically, increases seepage rate temporarily because the force driving the water through the soil is greater while the barometric of the air in the soil and that of the atmosphere are being equalized. However, this effect cannot be considered as important. Gupta and Swartzendruber (11) in experiments relating entrapped air content to variation in hydraulic conductivity K, applied a static gauge pressure to the soil-water system inside the permeameters over a fairly narrow range of 55 to 70 cm of mercury (22 to 28 in. Hg) and concluded that $\Delta V/\Delta P$, the change in volume per unit of applied pressure, may be a more sensitive indicator of entrapped air than is K because of the gradual decline in $\Delta V/\Delta P$ for constant K. Since the maximum variation in 1971 in the barometric pressure at Twin Falls was from a high of 30.62 inches of mercury to a low of 29.46 inches of mercury, this effect must be considered negligible.

Salts contained in the soil and water may have a marked effect on seepage rate. The biological processes that take place when water is passed through a soil may change the hydraulic conductivity. These two effects will be discussed in the following two sections.

Hydraulic Conductivity Related to Swelling of Soil

Because hydraulic conductivity appears as the proportionality factor in the Darcy equation, it is often erroneously thought to be a constant. It is constant for stable porous materials that are not subject to changes in pore configuration, but for soils hydraulic conductivity is not a constant. The hydraulic conductivity of soils is subject to variations that arise from the chemical interrelationships between the soil and water. Hydraulic conductivity for a given soil may change several fold due to changes in either exchangeable cation composition of the soil or electrolyte concentration of the water. These changes may take place as a result of differences in the chemical condition in the soil from one point to another or may occur with time at a given point as water flows through the soil. These changes, which take place during the operational practices associated with irrigation (and drainage) are of considerable importance from a practical standpoint. Since permeability is a measure of the nature, size and configuration of the pores of the medium, a change in permeability with time simply means that the porous medium is changing. In view of this, the factors and processes that cause such changes take on added significance in the application of permeability measurements to practical problems.

Several research workers have investigated the effect of electrolyte concentration on soil permeability, e.g. Bodman and Fireman (3), Reeve et. al., (24), Quirk and Schofield (23), Brooks et. al., (5) and more recently McNeal, et. al., (17, 18, 19).

All of them are of the opinion that the use of water of very low electrolyte content could result in soil sealing to such an extent that reclamation would not be possible.

McNeal (18) has shown that clay and fine silt fractions from certain soils exhibit swelling characteristics which significantly reduce hydraulic conductivity upon percolation of high sodium, low salt solutions. It means that hydraulic conductivity measurements are useful for quantitative studies of soil response to changes in the chemical properties of irrigation waters since they reflect the water movement behavior.

This thesis reports on quantitative studies to evaluate the changes in the hydraulic conductivity of a Portneuf silt loam soil when subjected to percolation of waters with varying sodium and total salt concentrations.

Effects of Microorganisms on Permeability

Experimental work done by Allison (1) has shown that intrinsic permeability of soils under prolonged application of water change with time. In his laboratory work with soil cores he found that the curve which represents its variation is an S-shaped curve (Figure 2) that can be explained as follows:

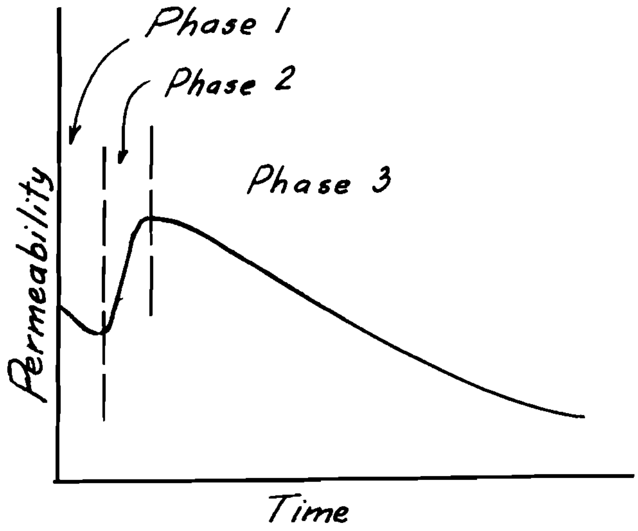

Figure 2. Changes in permeability of soils during long submergence.

"a. The initial decrease in permeability or infiltration rate is believed to be caused by dispersion and swelling of the soil particles. This is much more pronounced in some soils than others.

"b. The increase in permeability following the initial decrease accompanies the elimination of entrapped air from the soil. This air is slowly dissolved in the water passing through the soil.

"c. The gradual decrease in permeability that follows is due primarily to biological activity in the soil."

This decrease in intrinsic permeability, or in other words, the reduction of conductivity, may be attributed partly to the dispersion of aggregates due to microbial attack and to the clogging of the pores by products produced by microbial activity.

Brockway and Worstell (4) concluded the same in their report after measuring over a two-month period the conductivity of an impeding layer formed by the accumulation of natural silt layers on the bottom of an operating canal.

More recently Martin and Richards (16) studied the effect exerted upon soil physical properties by polysaccharides and concluded that changes may be greatly influenced by metal irons, specifically Fe and Al.

It is interesting to note they inferred that some polysaccharides increased aggregation but did not affect hydraulic conductivity, although it is further possible that some of the polysaccharides formed gels on the soil surfaces which partially blocked pore spaces and reduced hydraulic conductivity.

CHAPTER III

THEORY

McNeal and Coleman (18) suggested two factors which might be responsible for the reduction in hydraulic conductivity of a soil when leached with water having a very low salt concentration, as the typical concentration of irrigation water.

One factor is the swelling of the clay particles. This decreases the size of the large pores in the systems and thus decreases permeability. The other possible factor is the dispersion of the clay platelets, which can then move and block pores and channels in the soil, thus reducing permeability.

The present chapter deals primarily with McNeal's method (20) for predicting the hydraulic conductivity of soils in the presence of a wide range of mixed-salt solutions.

Clay Mineralogy

The percentages of sand, silt, and clay determines the texture of the soil. The physical properties and the chemical composition of the large and small particles differ greatly. The coarse separates (stones, gravel, and sand) act as individual particles. They are composed mainly of rock fragments of such primary minerals as quartz.

Because of their size, these large particles have low specific surface (surface area per unit mass). Most of the important chemical and physical-chemical reactions in soils take place at the surface of the particles. The amount of such surface, therefore, strongly affects the ability of soils to react chemically.

The properties of silt particles are intermediate between those of sand and the clays, but mineralogically silts are more like sand because they are composed largely of primary minerals. Silt particles have greater chemical activity than sand because of their higher specific surface.

The clay fraction is the one that controls most of the important properties of a soil. The classification of the clay minerals is based on the structure and composition of the various clay minerals. This tentative classification of clays according to Grim (10) and Marshall (15) and some information concerning hydration, are given in Table 1.

TABLE 1

Clay Classification According to Grim and Marshall

	Group Names	Ratio of number of silica to alumina layers	Hydration Characteristics
Layer-type lattice (typical shape is plate-like)	Kaolinite	1:1	Compact sheets, no internal (structural) hydration.
	Montmorillonite	2:1	Expands and contracts markedly with adsorption of water between clay sheets.
	Vermiculite	2:1	Expansion restricted.
	Illite	2:1	Hydration between packets of sheets
	Chlorite	(Ordered stacking of alternate layers of different types)	Some hydration.
Chain-type lattice (typical shape is rod or needle like)	Fibrous clay	(Not appropriate).	Open porous structure; can absorb water internally without expansion.

Ionic substitution of Al^{+++} for Si^{++++} and Mg^{++} for Al^{+++} are common in minerals of the 2:1 type. Such substitution destroys the balanced charge condition of the idealized structure and gives the clay mineral crystal a negative charge. Some negative charge also comes from unsatisfied bonds at the edges of clay mineral crystals.

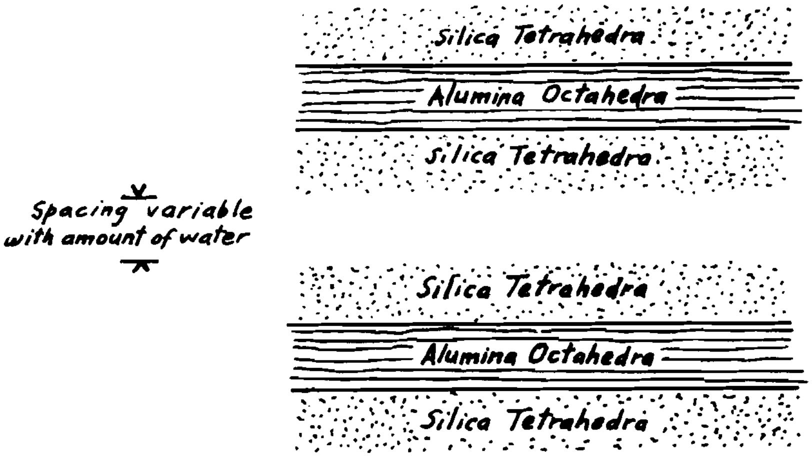

Figure 3. Crystal unit of montmorillonite clays.

The negative charge of the clay mineral causes the clay particles to react with other charged particles, ions, and with dipolar molecules, such as water. The attraction between the negatively charged clay and such positive ions as H^+, Ca^{++}, Mg^{++}, and K^+ is one of the most important properties of a soil.

The attracted ions are held in a state of dynamic equilibrium with similar ions in the soil solution and can be replaced or "exchanged" from the soil particle in response to changes in concentration in the soil solution. This process of ionic exchange is a process of fundamental importance in soil management.

The charged clay surfaces together with their associated exchangeable ions also react with water molecules, which become oriented when they are present in the strong electric field near the charged surfaces. The resulting layers of oriented water molecules give the characteristic properties of plasticity, cohesion, and shrinkage to clays and soils that contain large amounts of clay.

As far as clays are concerned the cation-exchange-capacities (CEC)[1] of the montmorillonite and vermiculite-like minerals, found in Midwestern soils and soils of the dry areas, are large.

Exchangeable-Sodium Percentage (ESP)

Calcium and magnesium are the principal cations found in the soil solution and on the exchange complex of normal soils in arid regions. When excess soluble salts accumulate in these soils, sodium frequently becomes the dominant cation in the soil solution. Thus, sodium may be the predominant cation to which the soil has been subjected, or it may become dominant in the soil solution, owing to the precipitation of calcium and magnesium compounds. As the solution becomes concentrated through evaporation or water adsorption by plants, the solubility limits of calcium sulfate, calcium carbonate, and magnesium carbonate are often exceeded, in which case they are precipitated with a corresponding increase in the relative proportion of sodium. Under such conditions, a part of the original exchangeable calcium and magnesium is replaced by sodium.

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[1] CEC of a soil is the quantity of positive ions necessary to neutralize the negative charge of a unit quantity of soil, under a given set of conditions. Usually is expressed as meq. of cations required to neutralize the negative charge of 100 g. of soil.

The degree of saturation of the soil exchange complex with sodium is called the exchangeable sodium percentage and may be calculated by the formula:

$$\text{ESP} = \frac{\text{Exchangeable sodium (meq./100 g. soil)}}{\text{Cation-exchange-capacity (meq./100 g. soil)}} \text{ X } 100 \qquad (4)$$

Sodium-Adsorption-Ratio (SAR)

In the past the relative proportion of sodium to other cations in an irrigation water usually has been expressed in terms of the SSP. However, the U. S. Salinity Laboratory (30) has developed the "sodium-adsorption-ratio" (SAR).

$$\text{SAR} = \frac{Na^{+}}{\sqrt{\left(\frac{Ca^{++} + Mg^{++}}{2}\right)}} \qquad (5)$$

in which:

Na^{+}, Ca^{++}, and Mg^{++} represent the concentrations in meq/liter of the respective ions.

The sodium adsorption ratio has statistically the best-fit empirical relationship to the ESP of the soil. This relationship between the soluble ions in the water that will remain at equilibrium with a given exchangeable sodium level in the soil has proven to be a good, if incomplete, index of one phase of irrigation water quality, indicating how and to what extent a given water containing excess sodium might change the permeability and structural stability properties of the soil. In general, the higher the SAR, the greater the adverse effects on permeability and other indices of soil structure.

McNeal, using the fact that in addition to its dependence on other factors, soil hydraulic conductivity commonly depends both on the exchangeable-sodium-percentage (ESP) of the soil and on the salt concentration of the percolating solution derived an expression which permits predicting the hydraulic conductivity of soils in the presence of mixed-salt solutions. He found a good inverse correlation between the hydraulic conductivity of soils high in 2:1 layer silicates (with the most labile hydraulic conductivities being exhibited by those soils containing the most montmorillonite) and the swelling of extracted soil clays in comparable solutions.

Prediction of Soil Hydraulic Conductivity

Function Relating Hydraulic Conductivity and Swelling

In view of the observed correlation of hydraulic conductivity with the swelling of extracted soil clays, McNeal (20) developed a function which related clay swelling and hydraulic conductivity decreases through a family of curves, each one representing a given exchangeable-sodium-percentage (ESP)[2] for a given soil.

The empirical expression is:

$$1 - y = cx^n / (1 + cx^n) \tag{6}$$

in which:

y is relative soil hydraulic conductivity $\frac{K_i}{K_o}$. Dimensionless.

x is a swelling factor. Dimensionless.

c,n are constants for a given soil within a specified range of ESP values. Dimensionless.

Values of n in equation (6) have been found to depend primarily on the soil ESP. As a first approximation, acceptable n values are:

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[2] For conversion of ESP into SAR we can use the equation or nomograms provided by the U. S. Salinity Laboratory Staff (30).

TABLE 2

Values of n for Different Soil ESP

	ESP < 25	25<ESP<50	ESP>50
n	1	2	3

The values of c and x should eventually be predictable from a knowledge of soil mineralogy and other soil properties. In practice, however, a common montmorillonite fractional content of 0.10 (10% montmorillonite on a whole soil basis) can be assumed for all soils. Any differences between the actual and assumed montmorillonite contents of the soil can then be incorporated into the multiplicative constant c':

$$c' = c \left(\frac{f_{mont} \quad actual}{f_{mont} \quad assumed} \right)^n \tag{7}$$

in which:

f_{mont} is the percentage of montmorillonite on a whole soil basis. The procedure can thus be used on soils for which no mineralogical information, or at best only qualitative information, is currently available. If enough information is available c' should be determined and used instead of c in equation (6).

Calculation of Swelling

Soils swell because they adsorb water. The mobility of soil-adsorbed water is less than that of nonadsorbed water. As a result, swelling reduces the width of pore channels available to macroscopic flow. The measure of swelling depends upon the electrolyte concentration and composition of ambient solution.

The interlayer swelling of montmorillonite in mixed-salt solutions is described according to McNeal by a "domain" model. In this model, mixed Na-Ca clays were considered to consist of discrete Na- and Ca-regions, with only the Na- regions swelling at low salt concentrations. Using this model, interlayer swelling can be calculated from the expression:

$$x = (f_{mont}) (3.6 \times 10^{-4}) (ESP^*) (d^*) \qquad (8)$$

in which:

f_{mont} is the weight fraction of montmorillonite in the soil. Dimensionless.

ESP^* is adjusted ESP. Dimensionless.

d^* is adjusted interlayer spacing. Å.

The last two variables must be determined by the following formulas:

$$ESP^* = \text{soil ESP} - (1.24 + 11.63 \log C_o) \qquad (9)$$

in which:

C_o is total salt concentration of the ambient solution, in meq/liter.

and

$$d^* = 356.4(C_o)^{-1/2} + 1.2 \quad (\text{for } C_o < 300 \text{ meq/liter}) \qquad (10)$$

or $$d^* = 0 \quad (\text{for } C_o > 300 \text{ meq/liter})$$

The 3.6×10^{-4} factor results from the following deductive reasoning:

$$\frac{(800 \times 10^4 \text{ cm}^2/\text{g}) \ (90\% \text{ internal surface}) \ (10^{-8} \text{ cm/Å})}{(100) \ (2 \text{ surfaces per unit of interlayer spacing})}$$

where:

800×10^4 cm^2/g is the average surface area of pure clay montmorillonite.

90% is the internal surface area of montmorillonite.

1 Å is equal to 1×10^{-8} cm.

It is obvious that 3.6×10^{-4} has as dimension $cm^3/g.\,\mathring{A}$. The x, the calculated interlayer swelling of soil montmorillonite, follows immediately from equation 8 and the unit dimension is cm^3/g. Since the density of water is essentially 1 g/cm^3, this swelling factor x can thus be considered unitless, and thus acceptable for direct use in equation (6).

Application of the present theory to disturbed soils for saturated flow is described in the next chapter.

CHAPTER IV

MATERIALS AND METHODS

Soil Studied

Field investigations of groundwater and seepage associated with canals were conducted by Brockway and Worstell (4) on the Unit "A" Main Canal (Northside Pumping Canal) and laterals of the A & B Irrigation District near Paul, Idaho during 1966. Since one of the objectives of this thesis is to determine whether naturally occurring seepage reduction exists due to the decrease of hydraulic conductivity of the silt layer in the aforementioned canal, the site selected for soil sampling was a section of the eight-mile reach of canal chosen for the location of ponding tests performed in the fall of 1965.

On April 16, 1971 samples and a soil profile log were taken in the right bank to a depth of 5.25 feet. The operating depth for the canal in this reach is about 3.0 feet and the total canal depth is 4.0 feet. The trapezoidal section has a bottom width varying from 14 to 8 feet and the design discharge varies from 240 cfs to 110 cfs.

The Main Canal is built in a Portneuf silt-loam soil and the soil profile in the area is consistent and includes primarily silt-loam soil with layers of moderate to highly consolidated silt-loam (hard-pan) throughout the mid-profile.

A study of the soil profile log determined to consider three different soil layers: A (0-24"); B (24"-42") and C (42"-63"). The soil chemical properties and the mechanical analysis of the three soil zones which were sampled for the study are presented in Tables 3 and 4, respectively.

TABLE 3

Chemical Properties of the 3 Different Soil Layers

Layer	pH[1]	Exchangeable Cations, meq/100g.			CEC meq/100g.	ESP	EC[2]	Cations[3] (Sat.Ext.)meq/l.		
		Ca + Mg	Na	K				Ca + Mg	Na	K
A	7.7	14.4	1.43	0.22	16.0	8.94	0.91	6.1	1.75	.19
B	7.9	9.9	1.12	0.20	11.3	9.91	0.73	6.0	0.98	.15
C	8.2	8.2	1.17	0.19	9.6	12.2	0.85	6.5	0.94	.15
Mixed M	7.9	9.2	1.44	0.20	10.9	13.2	0.77	6.5	1.54	.16

[1] pH of saturated soil paste (same as on chemical properties of saturation extracts).

[2] Electrical conductivity of saturation extract at 25°C in millimhos/cm.

[3] EC and Ca + Mg are from analyses of Portneuf soil from SRCRC, Kimberly, Idaho.

TABLE 4

Mechanical Analysis of the 3 Different Soil Layers

Layers	PERCENT		
	Sand $>50\mu$	Silt $2\text{-}50^{\mu}$	Clay $<2\mu$
A (0-24")	16.4	62.0	21.6
B (24"-42")	17.4	69.0	13.6
C (42"-63")	20.4	72.0	7.6

The mineralogical properties of the Portneuf silt-loam soil had been determined previously by the Department of Soils, University of Idaho, and are listed in Table 5. It is necessary to point out the fact that those figures correspond to a Portneuf silt-loam soil from the Pocatello (Idaho) area. Therefore, some differences might be expected from samples taken close to Paul (Idaho), that could influence the results of this study.

TABLE 5

Clay fraction mineralogy[3]

	PERCENT	
	Coarse clay	Medium and fine clay
Montmorillonite	7 - 10	38 - 40
Kaolinite	8 - 12	4
Illite	79 - 80	58 - 60

Measurement of Hydraulic Conductivities with Different Solutions

Apparatus and Soil Placement

Hydraulic conductivity measurements were determined employing plexiglas permeameters. The chambers were cylindrical 8.5 cm. high by

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[3] Obtained by personal communication from Prof. G. C. Lewis, University of Idaho staff.

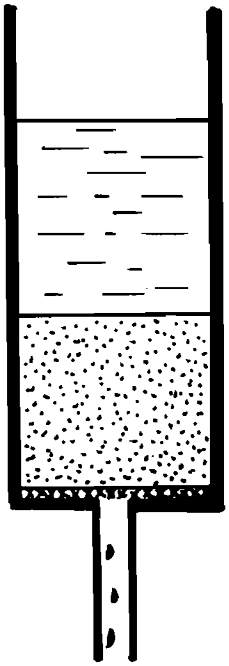


Figure 4. Permeameter used during experiments.

3.2 cm. ID (Figure 4). The effluent was drained from chamber through a length of tubing 3.5 cm. long which was fitted into a 3.0 mm. diameter outlet in the bottom of chamber. Fitted sections of 20-mesh copper screen were placed in the bottom of chamber and covered with fiberglass matting. Sufficient soil was placed in chamber to give approximately a 2.6 cm. depth of compacted material. The filling operation was accomplished by pouring the dry soil through a funnel with a long spout. The spout of the funnel was held above the soil level and raised as the filling preceded in one continuous operation. As the funnel was slowly withdrawn, a rotating motion was imparted to its lower end such that a minimum of segregation of particles or aggregates would occur.

Compaction of the air-dry, <1 mm. soil was carried out in the permeameters, covered with a 500 g. brass weight, by dropping each 27 g. sample 200 times through a distance of 2.5 cm. After compaction, the sample was covered with another layer of glass matting to prevent disturbance of the soil surface.

Experimental Procedure

Once the soil samples were placed in the permeameters and compacted to the desired average density, air was displaced (9) by passing CO_2 through each sample for a total of 15 minutes.

Two adjustable racks were used to hold 20 permeameters, 6 core samples from each layer A and B, and 8 corresponding to layer C.

After air was displaced from the samples with CO_2, they were immediately wetted with solution number I, a high salt-high sodium solution (C_0 = 500 meq/liter, SAR = 100). Leaching the soil with a solution like this one provides a measure of the maximum hydraulic conductivity of soil.

By then maintaining the same SAR while decreasing the salt concentration of the percolating solution to a relatively low value (Solution Number II, C_0 = 50 meq/liter) the relative hydraulic conductivity can be assessed at a point where significant interlayer swelling of soil montmorillonite should occur.

Both solutions contained 40 ppm. $HgCl_2$ to inhibit biological activity and a controlled hydraulic gradient of approximately two was maintained throughout the measurements.

The procedure for determining hydraulic conductivities for both treatments were identical. The 20 samples were run simultaneously with measurement periods for the 20 samples staggered at 30 second intervals to permit one person to take readings on the solution percolate. The volume of percolate that occurred hourly was recorded and terminated as soon as the volumes were approximately constant during five or six hours.

The experiments were conducted in an approximately constant temperature room, 75°F ±2. The temperature and the humidity were continuously recorded by a hygrothermograph.

The calculation of the hydraulic conductivity involves the use of the Darcy equation which is expressed in the following way:

$$Q = K\ i\ A = \frac{K\ h\ A}{L} = \frac{V}{\Delta t} \tag{11}$$

or

$$K = V\ L\ /\ A\ h\ \Delta t \tag{11a}$$

where:

K = hydraulic conductivity (cm/hr.).

V = volume of percolate in time Δt (ml.).

L = length of soil column (cm.).

A = cross-sectional area of the soil column (cm.^{2}).

h = difference in hydraulic head between the inflow and outflow ends of the soil column (cm.).

Δt = time interval for the volume of percolate, V, to pass through the soil (hour).

An average relative hydraulic conductivity $y = \frac{K_i}{K_o}$ was found for each layer which permitted calculation using equation (6) of three different c values, according to the three ESP ranges listed in Table 2.

This provides a set of c values to be used at the various ESP levels for the soil under consideration. These c values can then be used for predicting hydraulic conductivity decreases in the presence of all additional mixed-salt solutions for which an estimate of soil ESP, and hence of n and x, is available.

That was made with each layer considering salt concentrations of 1, 5, and 10 meq/liter.

Reversible Procedure

Once all the 20 samples were leached with the low salt-high sodium solution (sol. II), a procedure to determine if the process is reversible was established.

For that purpose 9 of the samples (3 of each layer) which had been previously wet with the appropriate solutions were saturated with a high salt solution [$CaCl_2$ (0.5N, SAR = 0)] and with distilled and irrigation waters. The volume of percolate during 5 days was recorded and the hydraulic conductivity calculated as before.

Examination of the Variation of Saturated Conductivity with Time

Apparatus and Soil Placement

Soil containers were made from plexiglass, 8.2 cm. I.D., and 19.5 cm. in length (Figure 5). Fitted sections of 20-mesh copper screen were placed in the bottom of the cylindrical chamber and covered with fiberglass matting. The screen was supported 1.2 cm. above the bottom of the cylinder by a series of plastic strips radially oriented to channel the effluent water toward the center outlet pipe which was 0.6 cm. I.D. and 2.5 cm. long.

Sufficient soil was placed in each chamber to give approximately 7.4 cm. depth of compacted material. The filling operation was exactly the same as used before.

Compaction of the air-dry, <2 mm. soil was carried out in the permeameters by dropping each one 20 times through a distance of 2.5 cm. onto a packing block, which is made from a heavy wooden block approximately 10 x 10 x 20 cm. A hole is made in the block to accommodate the outflow tube of the permeameter, and guide rods are mounted in the block

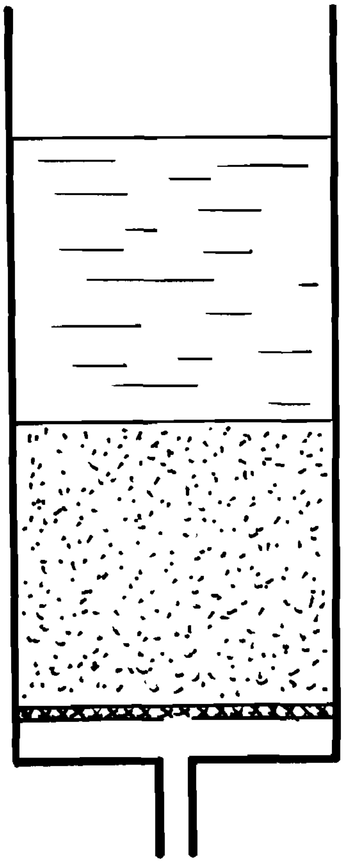


Figure 5. Soil column permeameter.

to keep the cylinder vertical and to insure square impacts. One rod is cut 2.5 cm. above the cylinder so that a finger placed over this rod gives a convenient index of height for the packing process. This column packer is similar to the equipment described by Richards (25).

The laboratory facility for determining hydraulic conductivity included 1/4 in. polyethylene tube, 1/4 in. O.D. needle valves, a Mariotte siphon apparatus for a constant head water supply, and a supply manifold to accommodate 12 soil columns. Figure 6 shows the laboratory set up with 4 operating columns.

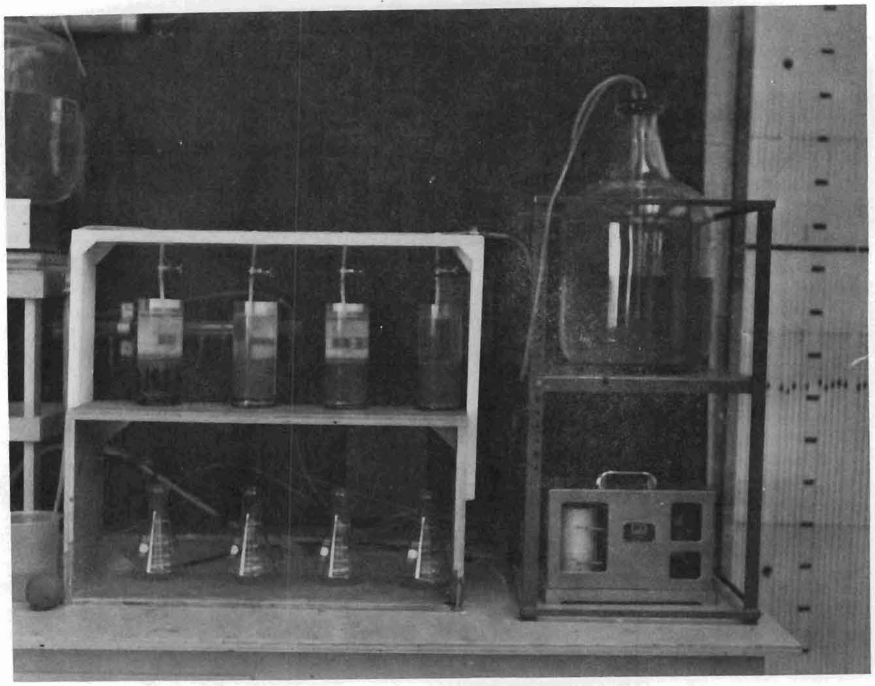


Figure 6. Laboratory equipment with tests in operation.

An analysis of the inflowing solution used in these tests is contained in Table 6. The influent solution was obtained from a ditch in the vicinity of the laboratory which contains water from the Snake River and is of the same quality as that diverted into the main canal of the Northside Pumping Division. The values shown are the average values calculated.

Experimental Procedure

Duplicate soil samples (columns 1 and 2 in Table 7) of layers A, B, and C and a mixture of them, M, held in 2 racks, were placed in the permeameters and air was displaced from the samples with CO_2.

TABLE 6

Water Analysis of the Ditch Water Sampled

Conductivity, EC x 10^6 @ 25°C	455
SAR	0.46
Percent Sodium	14.0
Suspended solids, ppm	70
Hydrogen-ion activity (pH)	8.3
Cations, meq/liter	
Calcium (Ca)	2.54
Magnesium (Mg)	1.23
Sodium (Na)	0.63
Potassium (K)	0.10
Anions, meq/liter or ppm	
Carbonate (CO_3)	0
Bicarbonate (HCO_3)	3.25
Sulfate (SO_4-S), ppm	14
Chloride (Cl)	0.61
Nitrate (NO_3-N), ppm	0.06

After that, they were immediately wetted with the usual irrigation water. A Mariotte siphon device was used to maintain a constant head on the top of the soil column and the flow rates through the columns were determined from measurements of the time and the volume of effluent. All the samples were run simultaneously and to determine the change in hydraulic conductivity with time, the columns were kept flowing continuously and conductivity was measured periodically over a two month period. Saturated hydraulic conductivity was determined from measured gradients and flow rates of the soil column and equation (11a), as before, was applied.

Four weeks after the beginning of the measurements the top layer (approximately 4 mm thick) of each soil column was removed and the flow rates were continuously measured in the same way.

TABLE 7

Soil column characteristics

LAYER	COLUMN	W(g)	L(cm)	Bulk Density $\rho(g/cm^3)$
A	1	541	7.40	1.38
	2	541	7.35	1.39
	ST1	541	7.30	1.40
	ST2	539	7.50	1.36
B	1	570	7.40	1.46
	2	570	7.35	1.47
	ST1	542	7.40	1.39
	ST2	567	7.50	1.43
C	1	574	7.40	1.47
	2	574	7.35	1.48
	ST1	571	7.50	1.44
	ST2	574	7.50	1.45
M	1	564	7.40	1.44
	2	564	7.35	1.45
	ST1	556	7.60	1.39
	ST2	566	7.50	1.43

The initial hydraulic conductivity was determined from the volume of percolate that occurred in the first-hour period immediately after the wetting of the soil samples.

The experiments were conducted in an approximately constant temperature room, 75°F ±2.

Effect of Microbial Activity on Hydraulic Conductivity

Apparatus and Soil Placement

The same type of permeameter described in the previous paragraph was used in this phase of the experiments. Also, the same method of transferring the soil was used (in order to prevent particle-size segregation) and the compaction and equipment employed was identical.

Two things, however, differ: 1) The water that was used and, 2) the soil which was subjected to a treatment.

The water supply in this case was again ditch water, with the same chemical properties of the water flowing in the Main Canal, but filtered to remove the particles in suspension and containing 40 ppm. $HgCl_2$ to inhibit biological activity.

The soil, for the same reason, was placed in the autoclave at 120°C during 24 hours in order to sterilize it.

Experimental Procedure

Duplicate soil samples, one for each layer, plus a mixture of them, were held in two racks and the same procedure described in the preceding paragraph was followed. (See Table 7 for ST1 and ST2 soil column characteristics).

The influence of micro-organisms and of their metabolic products upon the physical condition of the soil, especially in aggregating the finer soil particles (a problem of great importance in soil conservation) is becoming more and more clearly recognized. The growth of organisms in a fine-textured soil interferes with the downward movement of water whenever the soil pores become clogged with microbial bodies and their products. The microbiological population is largely distributed through the upper layers of the soil mass.

$HgCl_2$ was added to filtered ditch water for the purpose of minimizing the microbiological activity in the soil columns during the run. Bacteria were determined by plate counts with plating agar in all the ST1 soil columns.

CHAPTER V

RESULTS AND DISCUSSION

Measurement of Hydraulic Conductivities with Different Solutions

To meet the first objective of this thesis and test the theory set forth in objective 2, the surfaces of short soil columns were wetted as described earlier until the hydraulic gradient throughout each column was approximately equal to 2.0 and the conditions for applying equation (11a) were met.

Table 8 shows the experimental absolute and relative hydraulic conductivities found for each column as well as the average for each layer and the corresponding set of c values calculated using equation (6).

Figures 7a, 7b, and 7c show plots of predicted relative hydraulic conductivity (y) as function of soil ESP for the three different layers. Table 1-A to 3-A in the Appendix contain the refined data along with the respective formulas used.

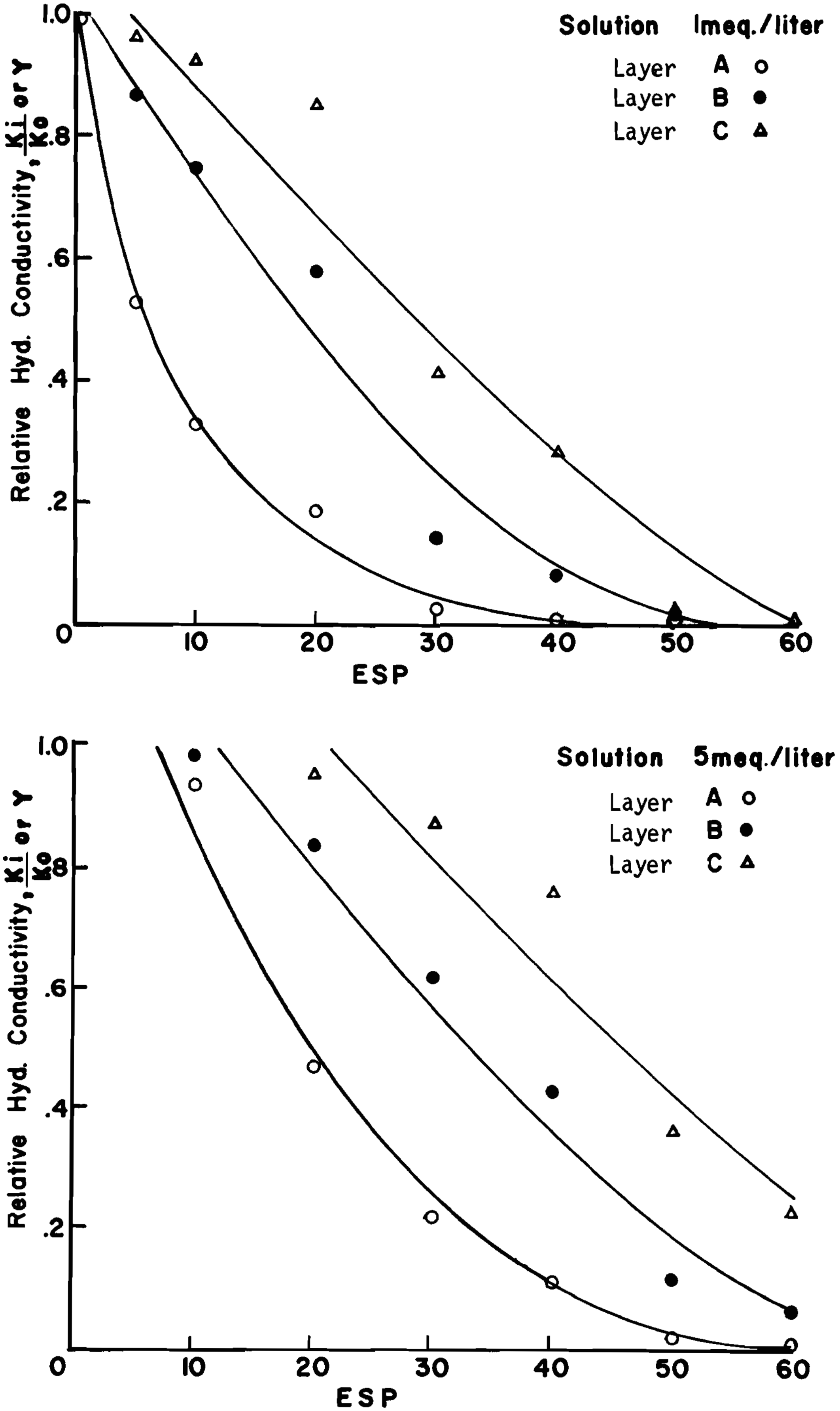
The points in Figures 7a, 7b, and 7c showing the reduction in hydraulic conductivity (y) for different values of soil ESP corresponding to layers B and C, are scattered. However, the good fit of experimental data to a smooth curve, indicated in the bottom curve of all the figures, (Figures 7a, 7b, and 7c) demonstrates that a reasonable relationship exists between relative conductivity and soil ESP for layer A, where there is a higher content of montmorillonite.

This procedure is less accurate on soils relatively low in montmorillonite. Calibration with a solution which gives a greater reduction in hydraulic conductivity may give more reliable results.

TABLE 8

Absolute and Relative Hydraulic Conductivities Obtained in the Laboratory Experiments and Corresponding Set of c Values

	LAYER		A			B			C	
		K_o	K_i	y	K_o	K_i	y	K_o	K_i	y
	1	.988	.433	0.44	.446	.374	0.84	.964	.849	0.88
REPLICATIONS	2	.970	.416	0.43	.519	.410	0.79	.973	.908	0.93
	3	.493	.215	0.44	.489	.400	0.82	.944	.937	0.99
	4	.489	.215	0.44	.525	.447	0.85	1.17	1.10	0.93
	5	.578	.248	0.43	.629	.499	0.79	1.07	1.06	0.99
	6	.553	.238	0.43	.507	.412	0.81	1.10	1.06	0.96
	7	-	-	-	-	-	-	1.29	1.20	0.93
	8	-	-	-	-	-	-	1.30	1.28	0.98
	$y_{ave.}$			0.43			0.82			0.95
c -	n = 1			18			3			0.7
	n = 2			248			43			10
	n = 3			3,424			589			137



Figures 7a and 7b. Relative hydraulic conductivity, y, vs. soil ESP.

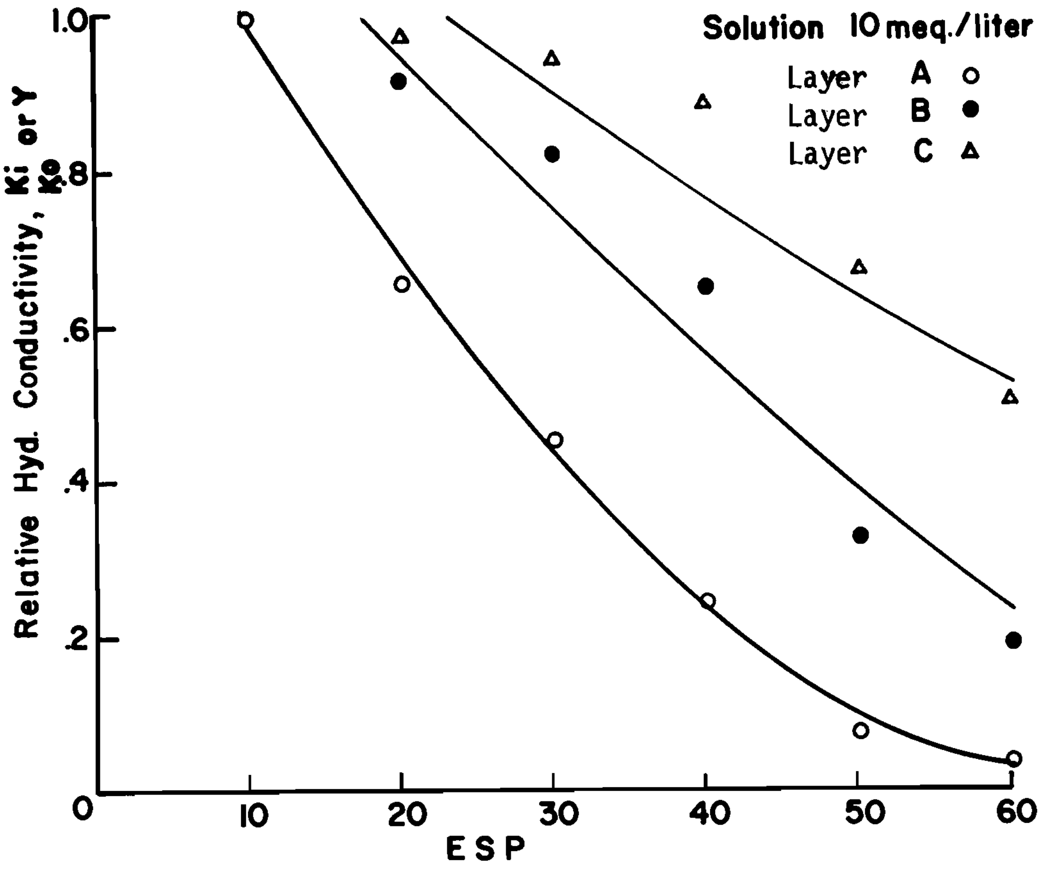


Figure 7c. Relative hydraulic conductivity, y, vs. soil ESP.

It is necessary to point out that since the mineralogical data available on the soils used is not for the specific soil tested, the determination of the effect of changes in f_{mont} cannot be determined.

Reversible Procedure

Tests run to determine the effect of introducing the high salt solution [$CaCl_2$ (0.5N SAR = 0)], and also distilled and irrigation water on soil samples previously subjected to the low salt-high sodium solution (sol. II), indicated that (See Table 9):

1) Introduction of 250 ml. of the high salt-solution ($CaCl_2$) failed to change the final low hydraulic conductivity within 4 to 5 days,
2) introduction of salt-free (distilled water) solution resulted in a marked (10 fold) reduction from the final low hydraulic conductivity obtained with the solution II,
3) use of Snake River irrigation water resulted essentially in the same reduction as with distilled water.

Hydraulic conductivities when reduced at low concentrations did not rebound to their original values upon applying the higher concentrations of the salts.

TABLE 9

Initial and Final Hydraulic Conductivities Obtained with the Percolation of a High Salt Solution, Distilled and Irrigation Water

LAYER	$CaCl_2$(.5N)		Distilled Water		Snake River Irrigation Water	
	K_o[1]	K_i	K_o[2]	K_i	K_o[2]	K_i
A	.160	.163	.215	.019	.248	.027
B	.247	.256	.374	.039	.400	.042
C	.96	1.04	.908	.092	1.06	.113

[1] K_o represents the initial hydraulic conductivity obtained immediately after percolation with $CaCl_2$(.5N).

[2] K_o is the final low hydraulic conductivity obtained with solution II.

Variation of Hydraulic Conductivity with Time

Using the Normal Irrigation Water and Soil

The changes in saturated hydraulic conductivity (K) with time in response to treatment with irrigation water is shown in Figures 8, 9, 10, and 11. Figure 8, presents the results for Layer A, while layers B, C and the mixture sample M are shown in Figures 9, 10 and 11, respectively.

The hydraulic conductivity was determined on a flexible schedule. When fast changes were expected, measurements were made daily and for slow changes every 3 to 6 days. The given hydraulic conductivity value plotted in Figures 8 to 11 is the average for the two permeameters over a selected time interval of measurement. The time value plotted in the same figures is the center of the time interval over which K is averaged for each permeameter.

The results of the first two samples, which correspond to layer A and B (See Figure 8 and 9), are quite similar. Treatment here resulted in decreasing the hydraulic conductivity from an initial value of approximately 0.70 to 0.17 cm/hr. The removal of the impeding layer did not increase the hydraulic conductivity in layer A and a very slight increase occurred in layer B.

Figure 10, corresponding to layer C with the lowest content in clay, shows a decrease in hydraulic conductivity from about 1.20 to approximately 0.46 cm/hr. when the top layer was removed. After that the hydraulic conductivity increased suddenly up to 0.71 cm/hr.; and subsequently, a further reduction continued with time. Its lowest value is 0.41 cm/hr.

FIGURE 8.

Hydraulic Conductivity vs. Time
Irrigation Water (non-sterile)

Layer A

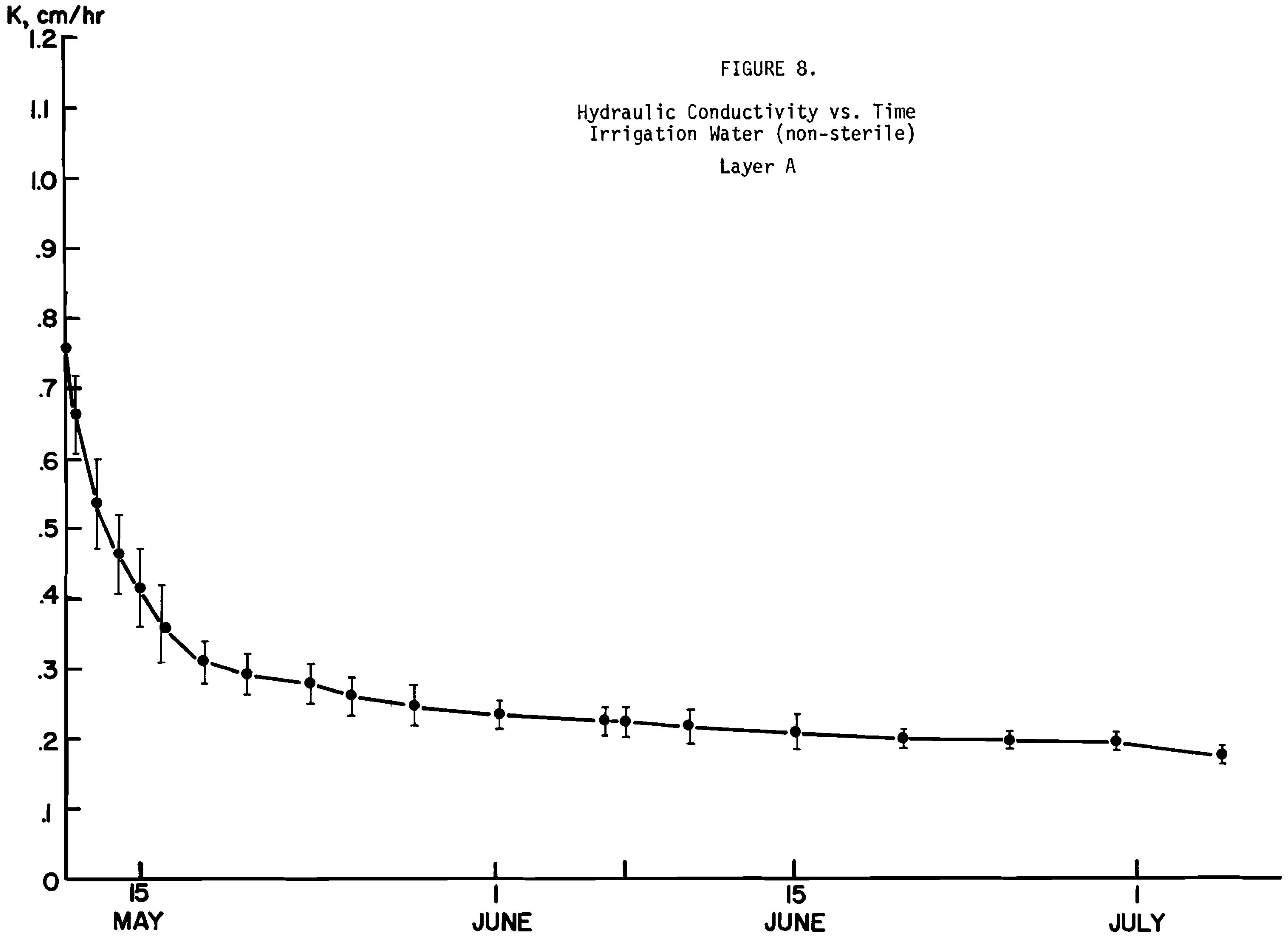
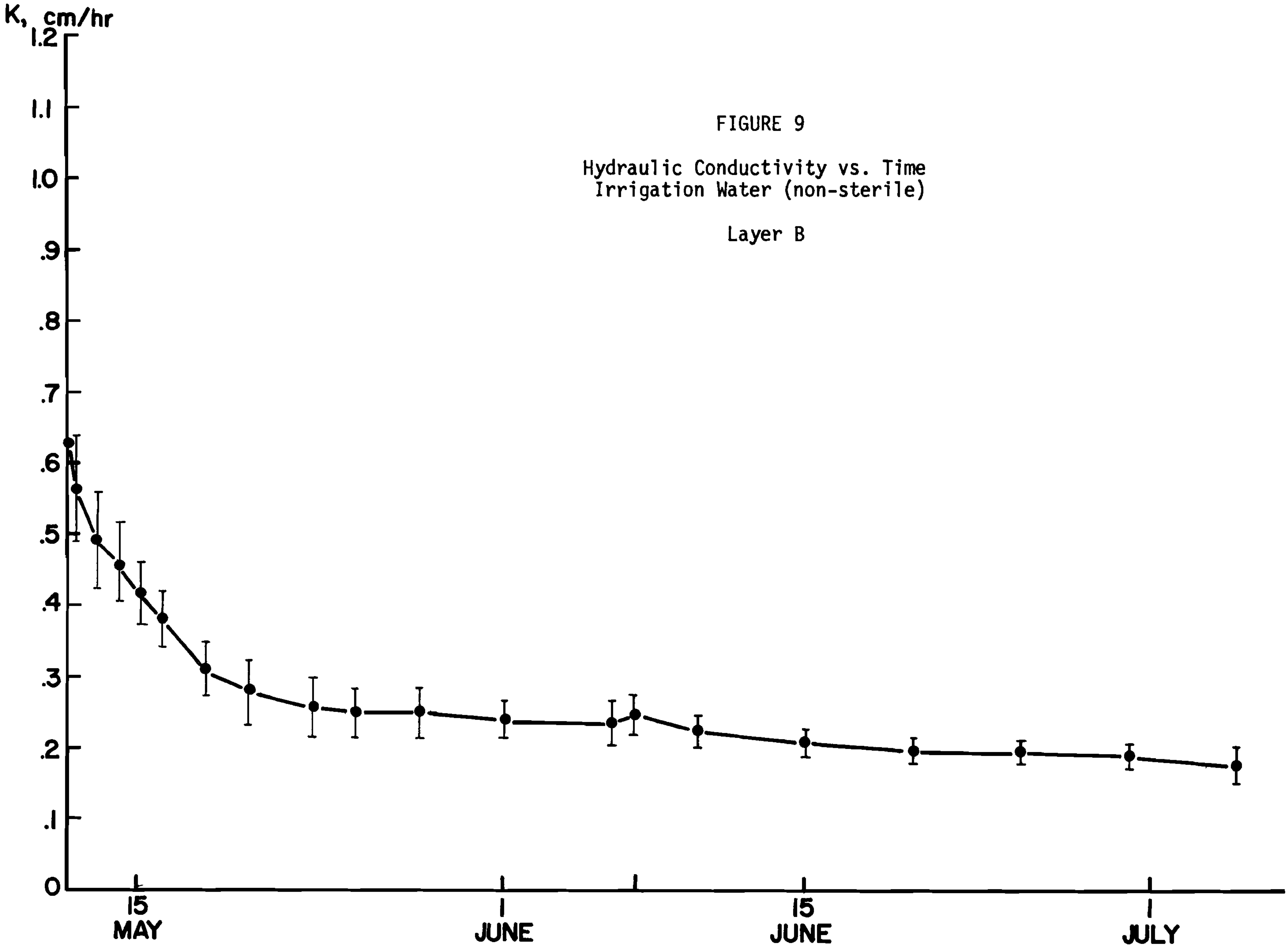


FIGURE 9

Hydraulic Conductivity vs. Time
Irrigation Water (non-sterile)

Layer B



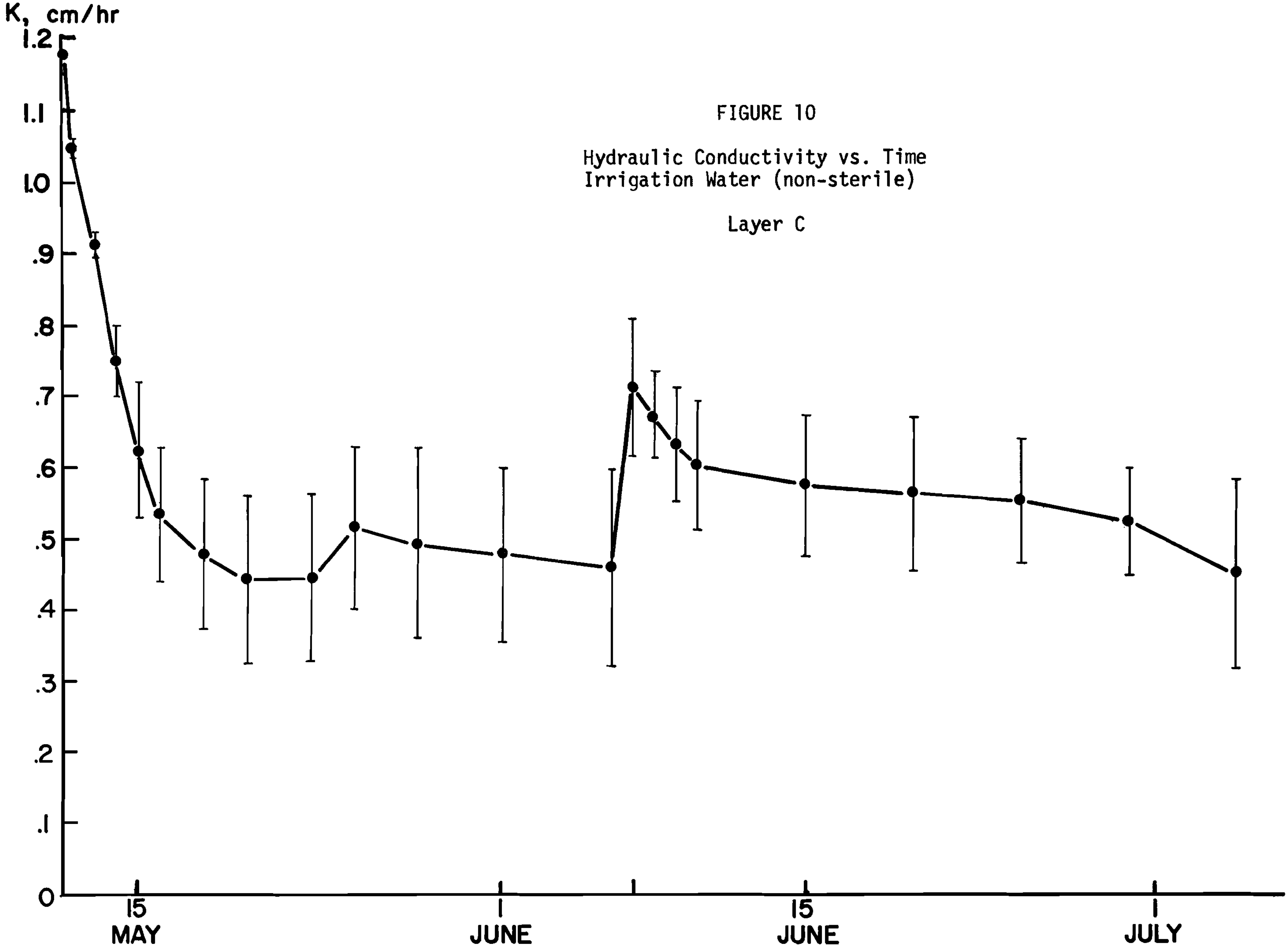


FIGURE 10

Hydraulic Conductivity vs. Time
Irrigation Water (non-sterile)

Layer C

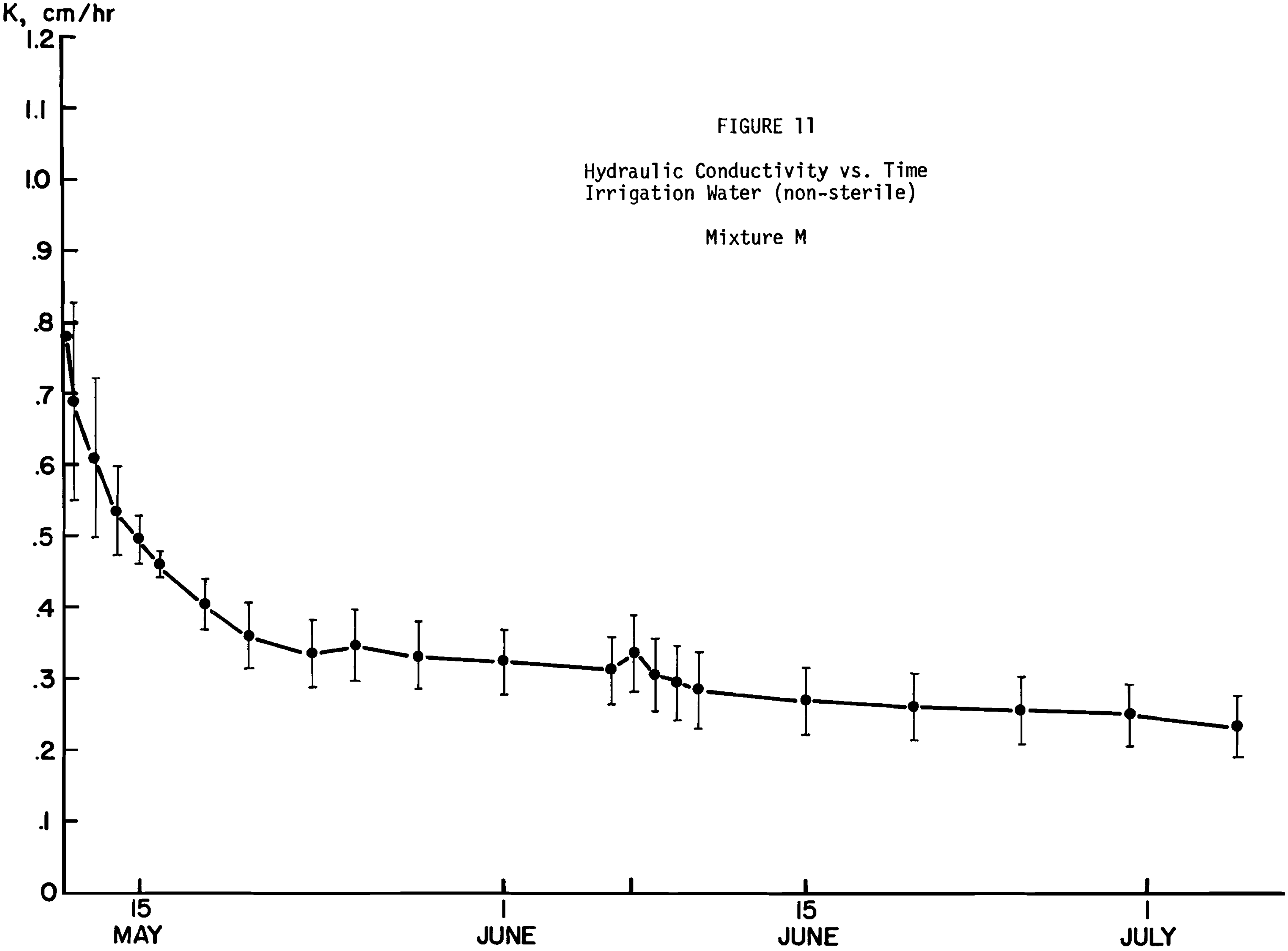


FIGURE 11

Hydraulic Conductivity vs. Time
Irrigation Water (non-sterile)

Mixture M

The sample represented by M produced K values intermediate between A, B, and C as anticipated (See Figure 11). The removal of the impeding layer originated a very slight increase in hydraulic conductivity.

The removal of the impeding layer in soil columns corresponding to Zone C resulted in an increase in the hydraulic conductivity. It did not appear in the soil columns A and B. This increase might be attributed to enough sample breakdown with wetting as ESP being the highest value in Zone C. Zone C is also the highest in silt content.

This differential behavior almost certainly arises from inorganic structural differences for the sample, or silting, rather than from microbiological sealing of the surface.

Using Sterile Soil and Sterile-Filtered Irrigation Water

The changes in soil saturated hydraulic conductivity K, within a treatment time interval of about three weeks and also in response to sterile-filtered water treatment, is shown in Figures 12, 13, 14 and 15. As in the preceding paragraph, each figure represents a layer, 12 for A, while the results of layers B, C and the mixture sample M appears in the Figures 13, 14, and 15, respectively. All four figures have the same K and time scales.

In this case the clay and fine silt particles in suspension are considerably reduced and bacterias are limited (almost nil) as determined by plate counts using plating agar. That is the reason the top 4 mm. layer was not removed and the columns were run only about three weeks, which was enough time to attain a constant hydraulic conductivity value.

The same steps given in the preceding paragraph in respect to the determination of the hydraulic conductivity as well as its plot on the K versus t plane were followed.

Layer A (Figure 12) shows a decrease in hydraulic conductivity from 0.82 to 0.36 cm/hr and Figure 13, corresponding to layer B, shows also a

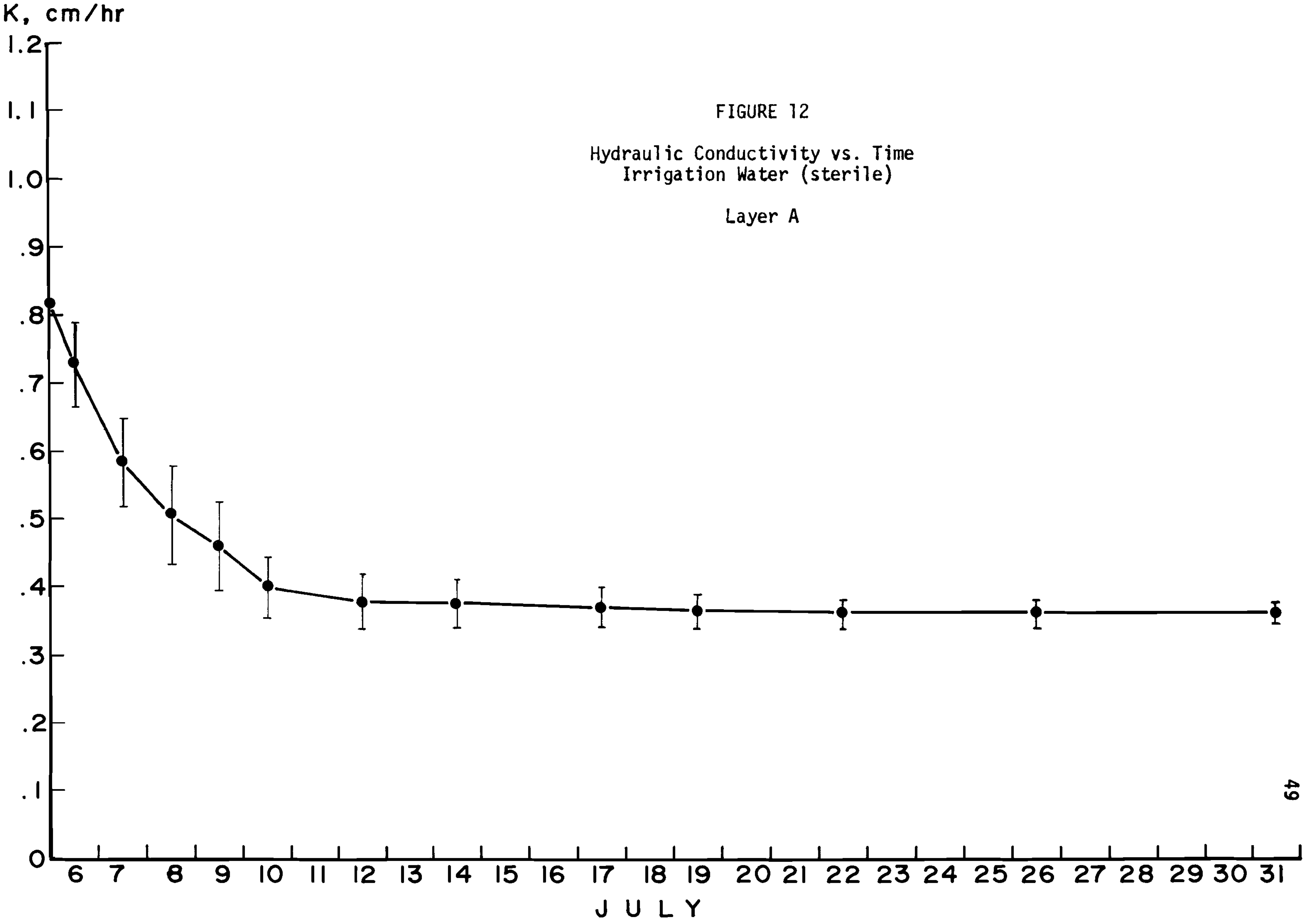


FIGURE 12

Hydraulic Conductivity vs. Time
Irrigation Water (sterile)

Layer A

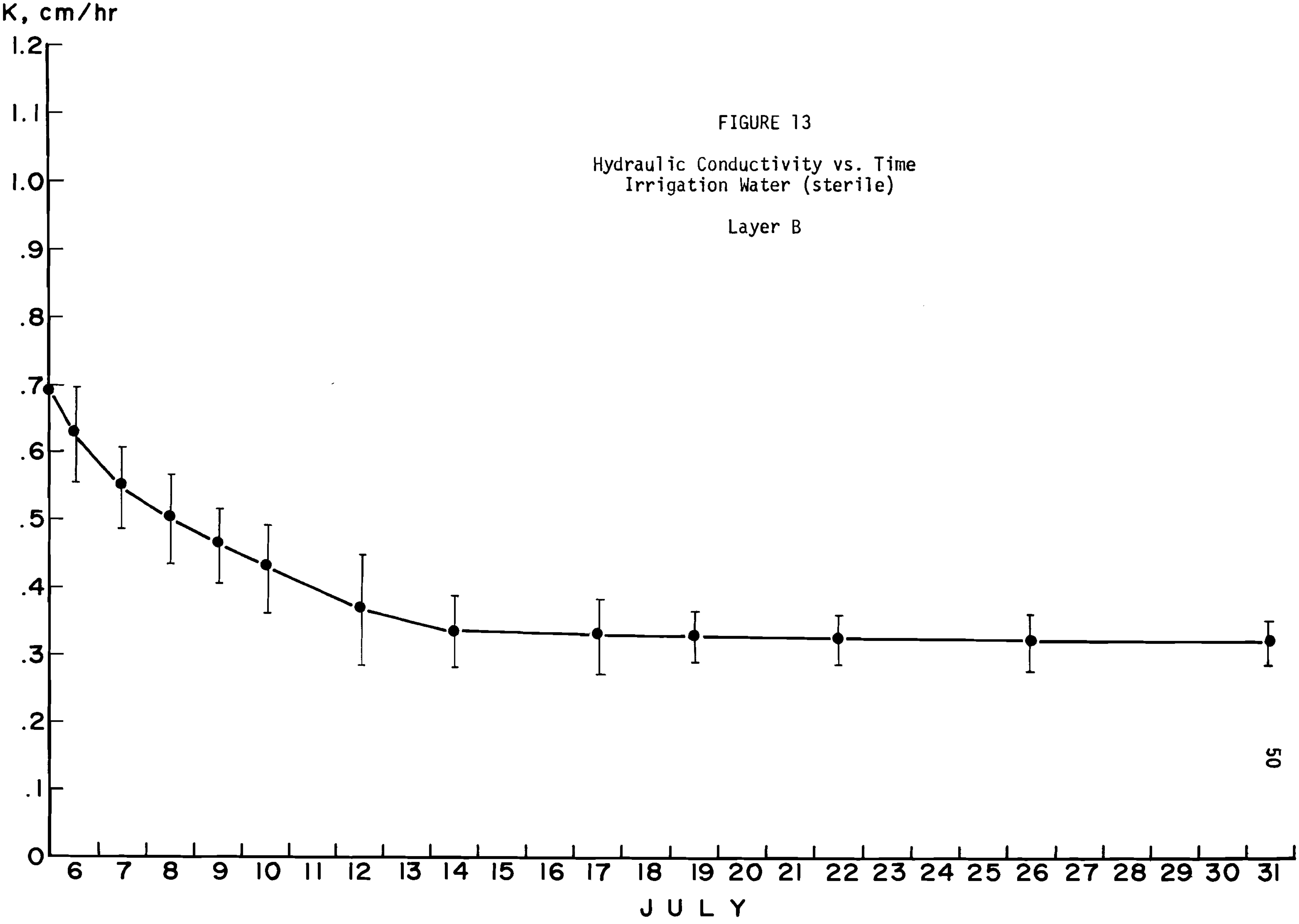


FIGURE 13

Hydraulic Conductivity vs. Time
Irrigation Water (sterile)

Layer B

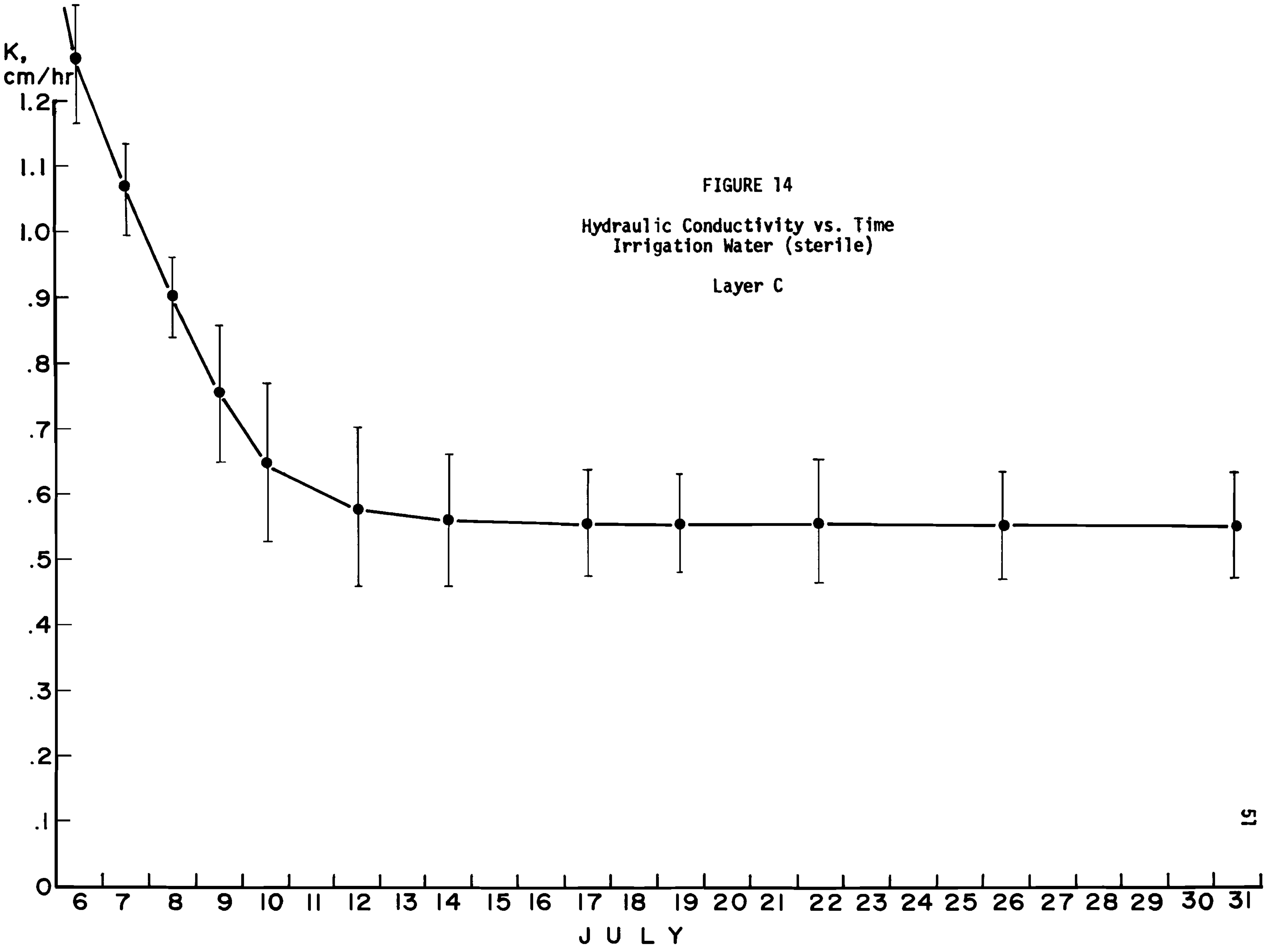


FIGURE 14

Hydraulic Conductivity vs. Time
Irrigation Water (sterile)

Layer C

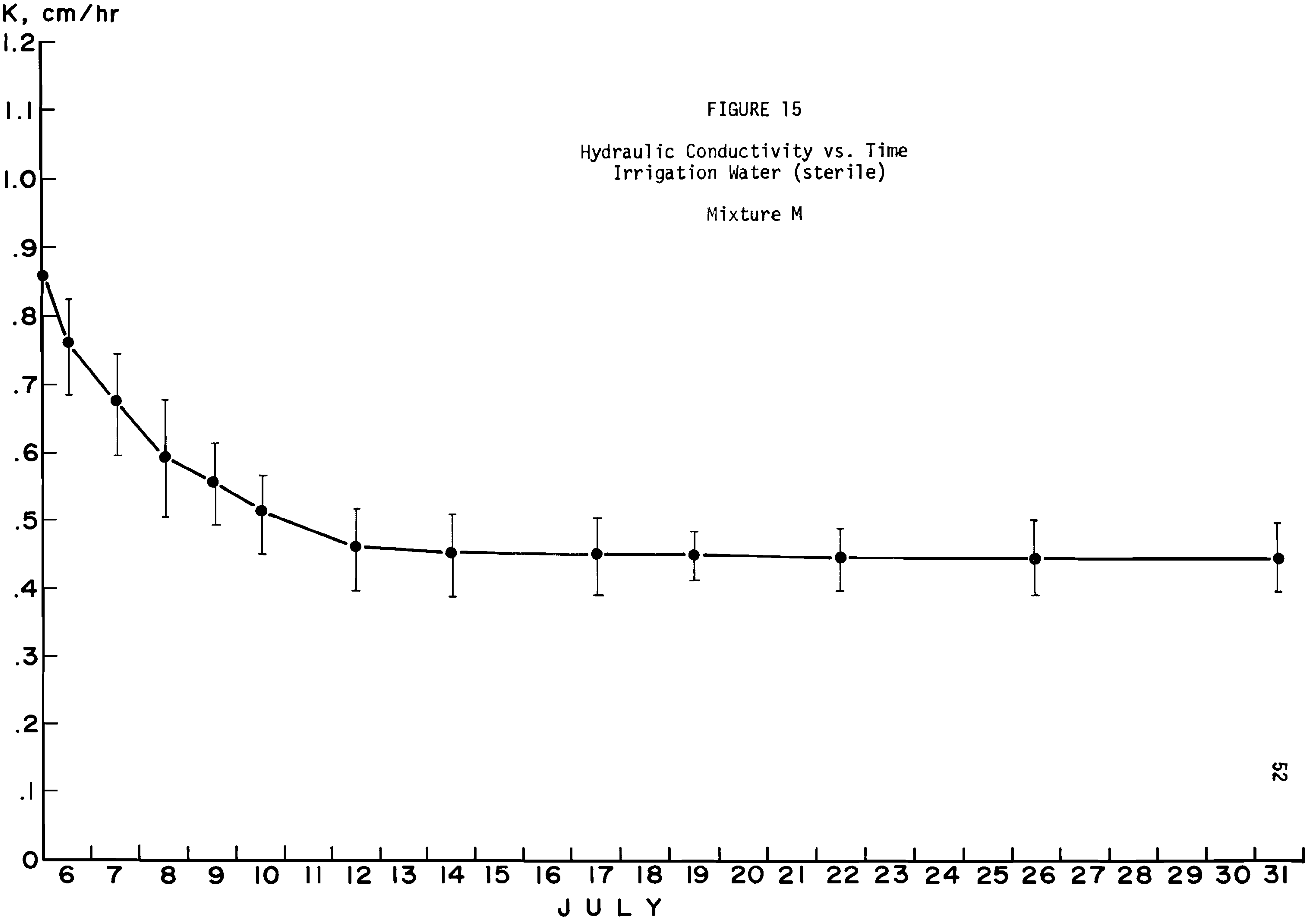


FIGURE 15

Hydraulic Conductivity vs. Time
Irrigation Water (sterile)

Mixture M

decrease in hydraulic conductivity in this case from about 0.70 to 0.32 cm/hr. Both results are relatively similar.

The third sample, which corresponds to layer C, shows a great decrease in hydraulic conductivity. Treatment here resulted in decreasing the hydraulic conductivity from an initial value of approximately 1.41 to 0.55 cm/hr. It is interesting to point out that although the initial hydraulic conductivity was high, the relative decrease was approximately the same (2.5 fold) as in layer A and layer B. Therefore, they should be lumped all together for discussion. The last sample represented by M has produced K values intermediate between A, B, and C.

An interesting detail to point out here is the different color of the percolation solution corresponding to each one of the samples. At the beginning, the percolation solution of sample A was dark yellow, while sample B was lighter and C was even more so. The percolation solution of sample M was intermediate between the other three samples.

As the runs proceeded the colors turned lighter and lighter, and 3 days after the beginning of the experiments the percolation solution was completely clear.

The color of the percolation solution is due to the release of organic matter present in the soil. Since layer A is the closest to the ground surface its content of organic matter is the highest, so its percolation solution is the darkest. The organic matter content in layer B is less than in A and greater than in layer C. Therefore, its percolation solution is lighter than in A and darker than in B.

There was no organic matter release when the soil was not placed in the autoclave. This is a result of some organic matter breakdown during autoclaving.

Since the colors are roughly proportional to the organic matter levels of the three layers, this is further evidence against microbial sealing as a mechanism for permeability decreases. Microbial growth should have been higher on the samples higher in organic matter (A and B), but these did not exhibit any appreciable increase in permeability when the top surface layer was stripped off.

Surface layers, when dealing with sterile soil and irrigation water, were not removed due to lack of time; however, it would have given further strength to the test of physical dispersion versus microbial sealing as a mechanism for permeability decreases.

Comparison of Predicted and Laboratory Conductivity Measurements

Figure 16, shows how the relative hydraulic conductivity of each of the layers (A, B, and C) changes with time. In other words, Figure 8, 9, and 10 are condensed in one graph, having considered only the first part of the experiment, before the removal of the impeding layer took place (equilibrium time).

Figure 17 is similar to Figure 16. It represents the variations of hydraulic conductivity with time when the tests were run with sterile-filtered irrigation water. Figures 12, 13, and 14 are then condensed in this new graph.

The measured total salt concentration of the irrigation water for both the sterile and unsterile series of tests was 4.5 meq/liter. Using an average ESP of 10 for the Portneuf-silt loam soils, the predicted relative hydraulic conductivity, as estimated from Figure 7b, should have been 0.83 for layer A and 1.00 for both layers B and C; or in other words, no decrease in the relative hydraulic conductivity due to swelling of the clay fraction is expected. Figure 17 shows relative hydraulic

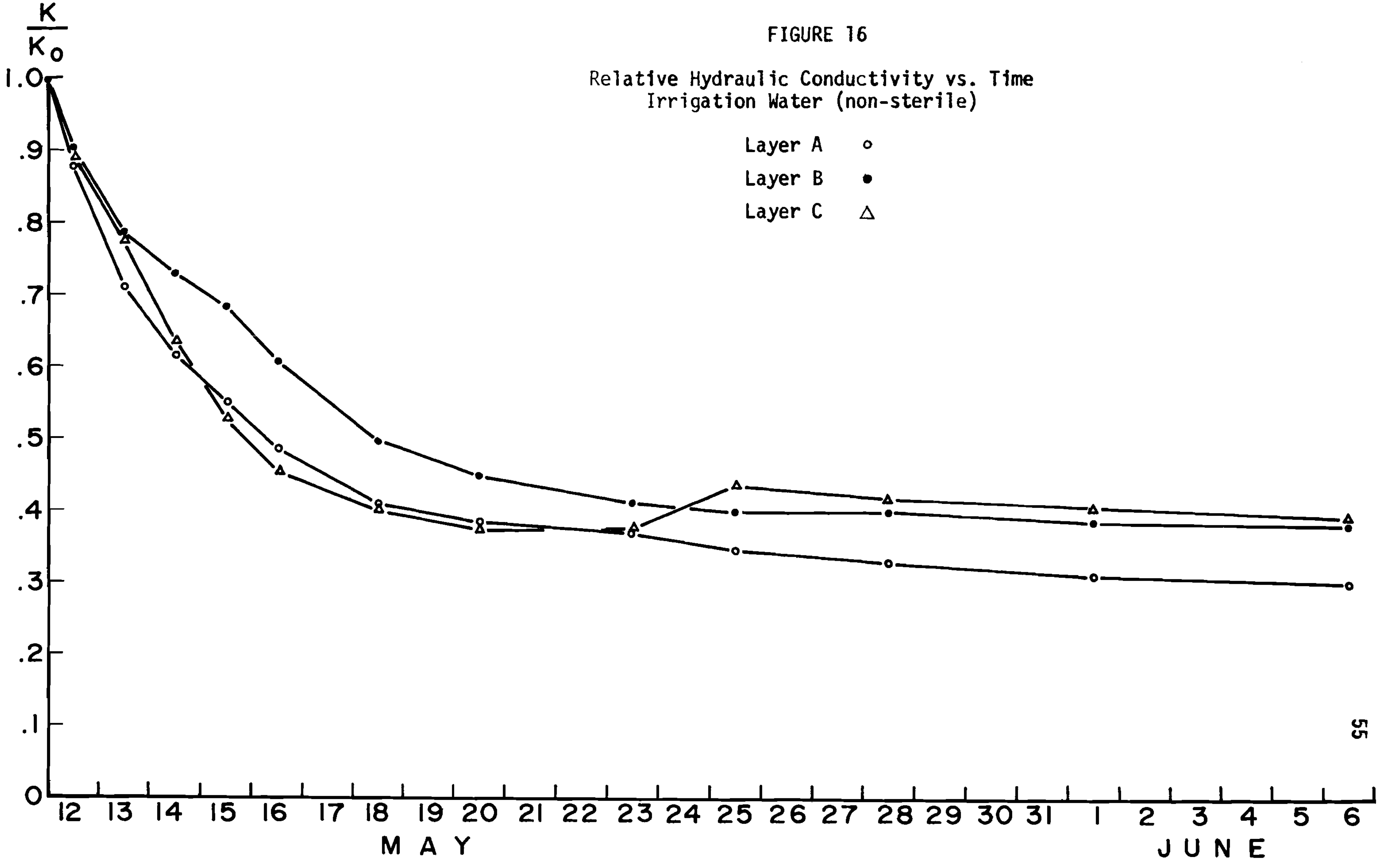


FIGURE 16

Relative Hydraulic Conductivity vs. Time
Irrigation Water (non-sterile)

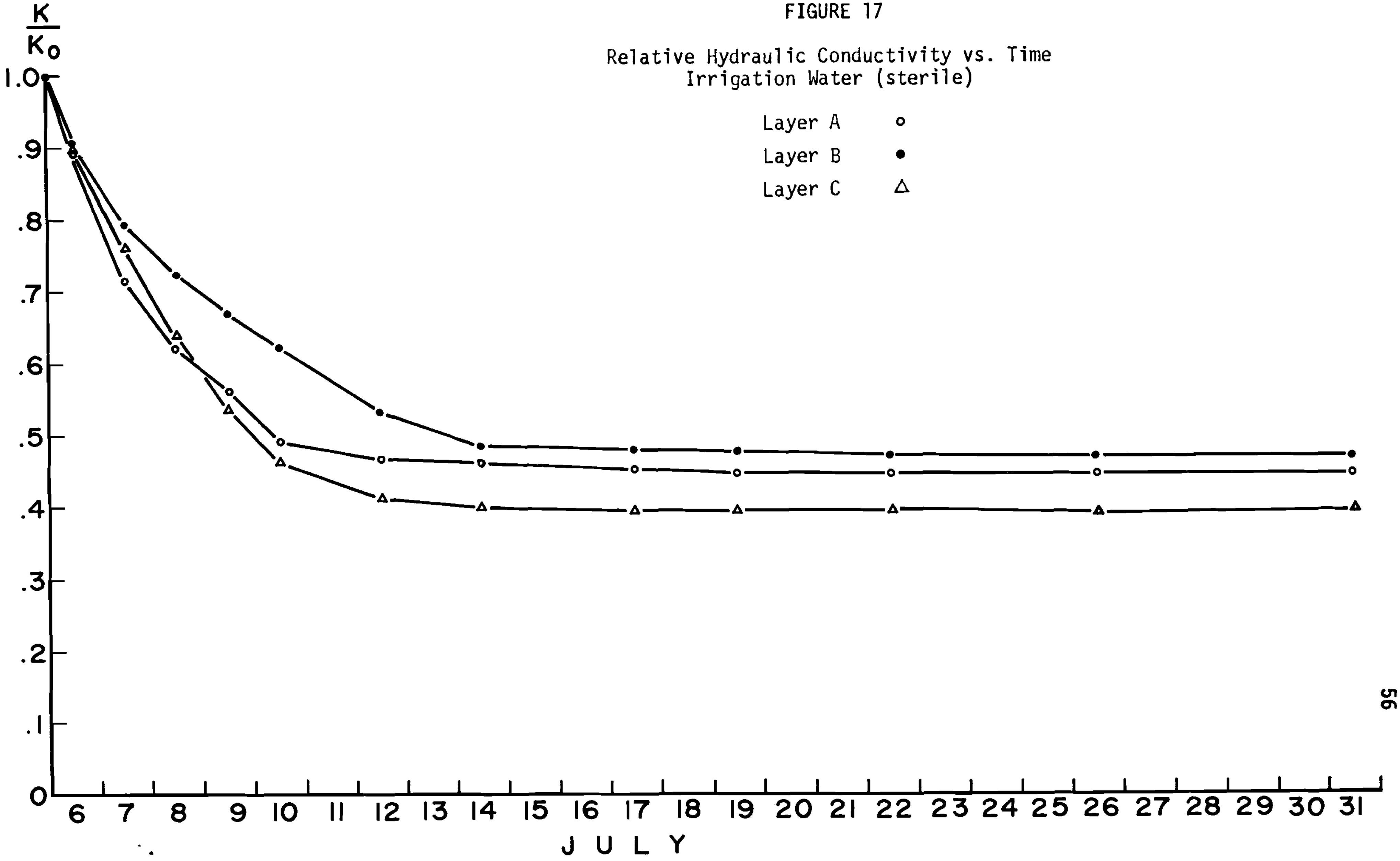


FIGURE 17

Relative Hydraulic Conductivity vs. Time
Irrigation Water (sterile)

conductivities of 0.44, 0.47 and 0.39 for layers A, B, and C, respectively. From a comparison of these results, we have to conclude there is a great difference. Since this difference cannot be attributed to different ways of packing because the bulk densities of the samples are similar, the only reasonable explanation for the lower values in the measured relative hydraulic conductivities in the presence of physical dispersion.

The measured relative hydraulic conductivity as shown in Figure 16 is 0.30, 0.38 and 0.39 for layers A, B, and C, respectively. Since Figure 16 represents the results with the non-sterile system, one might attribute the greater measured decreases in conductivity to microbial effects, clogging of soil pores due to sedimentation or mechanical dispersion. Figure 17 which represents the results of the test series using filtered sterile irrigation water on sterile soil columns shows similar results to the non-sterile series. In the filtered sterile series, the effect of sedimentation and microbial activities on the measured decreases in hydraulic conductivity can be eliminated. It can be expected that if there is any effect due to sedimentation and microbial activity that the decreases in hydraulic conductivity measured on the non-sterile system would be greater than on the sterile systems for all three layers. Data used for the above discussion appears in Table 10.

Figure 8 - 11 show the effect of the removal of the top 4mm. layer of the sample after an equilibrium hydraulic conductivity was reached. The removal of the top layer in the sample corresponding to zone or layer A did not cause any increase in the hydraulic conductivity; however, in sample B it was very slight and in sample C it was very significant since its values increase abruptly from 0.24 to 0.25 cm/hr and from 0.46 to 0.71

cm/hr, respectively. The sample M increased its hydraulic conductivity from 0.31 to 0.34 cm/hr.

TABLE 10

Initial K_o and Final K_i Hydraulic Conductivities (cm/hr) of Layers A, B, and C (From Figures 8-10 and 12-14).

	K_o		K_i (at equil.)		$y=K_i/K_o$	
	NAT.	STER.	NAT.	STER.	NAT.	STER.
A	0.76	0.82	0.23	0.36	0.30	0.44
B	0.63	0.70	0.24	0.32	0.38	0.47
C	1.18	1.41	0.46	0.55	0.39	0.39

There are two possible reasons for the differential behavior of sample C. The first one, which was discussed before, suggests that the difference is due to a structural change or dispersion in the top layer; and in the second one, change might be due to the differences in clay content.

Both reasons are not definitely proved. The first one because the data gathered is not sufficient; the second one because if the higher clay content were responsible a greater decrease in hydraulic conductivity would be expected for samples A and B. This, really, is not evident on a relative basis.

In general it can be stated with more assurance here that, likely neither microbiological sealing nor soil-chemical reactions nor silting effect are responsible for the reduction in hydraulic conductivity. Since the high silt soils apparently disperse readily, the decrease in hydraulic conductivity may result from this fact. The pores are then plugged with fine material. A limited swelling of the clay fraction can also be expected.

CHAPTER VI

CONCLUSIONS

The main process by which seepage in the canal reach investigated (the Main Canal of the Northside Pumping Division near Paul, Idaho) would decrease is by physical dispersion and the plugging of the pores with fine material with some limited swelling of the fine of clay fraction.

It is also likely that microbial activities are not responsible for the reductions in hydraulic conductivity. Although bacterial growth on the soil-water interface in the soil columns was not determined, it seems logical that if some non-mechanical effect such as microbial sealing does exist, the hydraulic conductivity should have progressively decreased with time. Neither can microbial sealing as a mechanism for permeability decreases can be explained using the fact of different colors for the percolate during the experiments with sterile soil and water.

Soil chemical reactions are probably not responsible for a significant part of the seepage reduction. The experiments following McNeal's method to evaluate solution concentration and clay composition effects on hydraulic conductivity indicated a slight decrease in it due to soil-water-chemical reactions only.

Layer A with the highest content in clay, and therefore, with the highest content in montmorillonite is the most suitable for the application of McNeal's method because of the swelling of clay plates. Less swelling is expected over layers B and C. It would be necessary to irrigate with water having a salt concentration of approximately 1 meq/liter to decrease the relative hydraulic conductivity to 0.35, 0.73 to 0.86 over layers A, B, and C respectively. Irrigation with a water concentration of 1 meq/liter is probably not likely because most irrigation waters have salt concentrations considerably in excess of this value.

Hydraulic conductivities when reduced at low concentrations did not rebound to their original values upon applying the higher concentrations of the salts. This lack of full reversibility indicates that direct effects of clay swelling are minor in causing resistance to water flow in these soils.

The increase in hydraulic conductivity with removal of the impeding layer in zone C, but not in zones A and B, is probably not due to microbiological sealing of the surface. This differential behavior likely arises from inorganic structural differences for the sample or differences in the clay content. The comparison between Figures 16 and 17, which show similar results, eliminated the possibility of silting and microbial activities.

Further work should be done in attempting to define what is the exact influence of microbial activity. Additional work should also be done, in order to gain a better understanding of the dispersion phenomena within the mass. The clay fraction mineralogy should be investigated using one of the modern techniques.

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NOTATIONS AND DEFINITIONS

A	is the cross-sectional area of a soil column. L^2.
Å	is a unit of length called angstrom equal to one ten-billionth of a meter. L.
c	is an empirical constant for a given soil within a specified range of ESP values. Dimensionless.
c'	is the adjusted c constant by the ratio of actual and assumed montmorillonite contents of a given soil. Dimensionless.
C_o	is the total salt concentration of the ambient solution. F/L^3.
d^*	is the adjusted interlayer spacing. L.
EC	is the electrical conductivity in mmhos/cm. unless otherwise specified.
ESP	is the exchangeable-sodium percentage. Dimensionless.
ESP*	is the adjusted ESP. Dimensionless.
f_{mont}	is the weight fraction of montmorillonite in the soil. Dimensionless.
g	is the gravitational acceleration constant. L/T^2.
h	is the difference in hydraulic head between the inflow and outflow ends of the soil column. L.
i	is the hydraulic gradient. Dimensionless.
K	is a coefficient called hydraulic conductivity. It is a function of the fluid viscosity as well as of the geometry of the medium. L/T.
K'	is a coefficient called permeability or "intrinsic permeability". It is a function of the geometry of the medium. L^2.
L	is the length or distance between two points in a porous medium in the direction of flow. L.
n	is a constant for a given soil within a specified range of ESP values. Dimensionless.
P	is pressure, which can be above or below atmosphere. F/L^2.
Q	is rate of flow of percolate. L^3/T.

SAR	is sodium-adsorption-ratio. $(F/L^3)^{1/2}$.
t	is time. T.
u	is the volume flux in the direction of flow. L/T.
V	is volume of percolate in time t. L^3.
x	is the swelling factor. Dimensionless.
y	is the relative soil hydraulic conductivity. Dimensionless.
Z	is the elevation of a point in a porous medium above a datum. L.
γ	is the specific weight of the fluid or weight per unit volume of fluid. F/L^3.
θ	is moisture content on a volumetric basis, the ratio of the volume of water to the total volume occupied by the soil. Dimensionless.
μ	is dynamic viscosity. FT/L^2.
ν	is kinematic viscosity. L^2/T.
ρ	is the mass density of the fluid. F/L^3
Δ	denotes a difference.

APPENDIX

Calculation of the Different c Values

Montmorillonite content assumed: $f_{mont} = 0.10$

Swelling factor: $x = (f_{mont})(3.6 \times 10^{-4})(ESP^*)(d^*)$

$x = 0.07245$

$ESP^* = 60 - (1.24 + 11.63 \log 50) = 39.00$

$d_{50}^* = 356.4\ (50)^{-1/2} + 1.2 = 51.60\ \mathring{A}$

	LAYER	$y = K_i/K_o$	n	c
$c = \frac{1-y}{x^n y}$	A	0.43	1	18
			2	248
			3	3,424
	B	0.82	1	3
			2	43
			3	589
	C	0.95	1	0.7
			2	10
			3	137

Calculation of the Adjusted Interlayer Spacing

$C_o = 1$ meq./l. $\quad d^* = 356.4\ (1)^{-1/2} + 1.2 = 357.6\ \mathring{A}$

$C_o = 5$ meq./l. $\quad d^* = 356.4\ (5)^{-1/2} + 1.2 = 160.6\ \mathring{A}$

$C_o = 10$ meq./l. $\quad d^* = 356.4\ (10)^{-1/2} + 1.2 = 113.9\ \mathring{A}$

Calculations of the Relative Hydraulic Conductivities

$$y = 1 - \frac{cx^n}{1 + cx^n}$$

TABLE 1-A

Calculations Corresponding to Layer A.

C_o = 1 meq./l.

ESP	ESP*	x	n	c	y
0	-1.24	-0.0160	1	18	1.0000
5	3.76	0.0484	1	18	0.5344
10	8.76	0.1128	1	18	0.3300
20	18.76	0.2415	1	18	0.1870
30	28.76	0.3702	2	248	0.0286
40	38.76	0.4990	2	248	0.0159
50	48.76	0.6277	3	3424	0.0012
60	58.76	0.7564	3	3424	0.0007

C_o = 5 meq./l.

ESP	ESP*	x	n	c	y
0	-9.37	-0.0542	1	18	1.0000
5	-4.37	-0.0253	1	18	1.0000
10	0.63	0.0036	1	18	0.9391
20	10.63	0.0615	1	18	0.4746
30	20.63	0.1193	2	248	0.2208
40	30.63	0.1771	2	248	0.1139
50	40.63	0.2349	3	3424	0.0220
60	50.63	0.2927	3	3424	0.0115

$C_o = 10$ meq./l.

ESP	ESP*	x	n	c	y
0	-12.87	-0.0528	1	18	1.0000
5	-7.87	-0.0323	1	18	1.0000
10	-2.87	-0.0118	1	18	1.0000
20	7.13	0.0292	1	18	0.6555
30	17.13	0.0702	2	248	0.4500
40	27.13	0.1112	2	248	0.2459
50	37.13	0.1522	3	3424	0.0765
60	47.13	0.1933	3	3424	0.0389

TABLE 2-A.

Calculations Corresponding to Layer B.

$C_o = 1$ meq./l.

ESP	ESP*	x	n	c	y
0	-1.24	-0.0160	1	3	1.0000
5	3.76	0.0484	1	3	0.8732
10	8.76	0.1128	1	3	0.7472
20	18.76	0.2415	1	3	0.5799
30	28.76	0.3702	2	43	0.1451
40	38.76	0.4990	2	43	0.0854
50	48.76	0.6277	3	589	0.0068
60	58.76	0.7564	3	589	0.0039

C_o = 5 meq./l.

ESP	ESP*	x	n	c	y
0	-9.37	-0.0542	1	3	1.0000
5	-4.37	-0.0253	1	3	1.0000
10	0.63	0.0036	1	3	0.9893
20	10.63	0.0615	1	3	0.8442
30	20.63	0.1193	2	43	0.6203
40	30.63	0.1771	2	43	0.4258
50	40.63	0.2349	3	589	0.1158
60	50.63	0.2927	3	589	0.0634

C_o = 10 meq./l.

ESP	ESP*	x	n	c	y
0	-12.87	-0.0528	1	3	1.0000
5	-7.87	-0.0323	1	3	1.0000
10	-2.87	-0.0118	1	3	1.0000
20	7.13	0.0292	1	3	0.9194
30	17.13	0.0702	2	43	0.8251
40	27.13	0.1112	2	43	0.6529
50	37.13	0.1522	3	589	0.3250
60	47.13	0.1933	3	589	0.1903

TABLE 3-A.

Calculations corresponding to layer C.

C_o = 1 meq./l.

ESP	ESP*	x	n	c	y
0	-1.24	-0.0160	1	0.7	1.0000
5	3.76	0.0484	1	0.7	0.9672
10	8.76	0.1128	1	0.7	0.9268
20	18.76	0.2415	1	0.7	0.8554
30	28.76	0.3702	2	10	0.4218
40	38.76	0.4990	2	10	0.2865
50	48.76	0.6277	3	137	0.0287
60	58.76	0.7564	3	137	0.0166

C_o = 5 meq./l.

ESP	ESP*	x	n	c	y
0	-9.37	-0.0542	1	0.7	1.0000
5	-4.37	-0.0253	1	0.7	1.0000
10	0.63	0.0036	1	0.7	0.9975
20	10.63	0.0615	1	0.7	0.9587
30	20.63	0.1193	2	10	0.8754
40	30.63	0.1771	2	10	0.7612
50	40.63	0.2349	3	137	0.3603
60	50.63	0.2927	3	137	0.2255

C_o = 10 meq./1.

ESP	ESP*	x	n	c	y
0	-12.87	-0.0528	1	0.7	1.0000
5	-7.87	-0.0323	1	0.7	1.0000
10	-2.87	-0.0118	1	0.7	1.0000
20	7.13	0.0292	1	0.7	0.9800
30	17.13	0.0702	2	10	0.9530
40	27.13	0.1112	2	10	0.8900
50	37.13	0.1522	3	137	0.6743
60	47.13	0.1933	3	137	0.5026