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Measuring and Predicting Steady State Infiltration Rates for Arizona Irrigated Soils

by

Mohammed Hussien Bagour

A Dissertation Submitted to the Faculty of the

DEPARTMENT OF SOIL, WATER AND ENVIRONMENTAL SCIENCE

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

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As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Mohammed Hussien Bagour

entitled Measuring and Predicting Steady State Infiltration Rates for Arizona Irrigated Soil

and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy

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Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

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Also, a note of thanks for Ms. Sheri Musil and Dr. A. Warrick who helped and advised me about soil physical measurements and allowed me to use their lab facilities.

DEDICATION

To my parents Hussien and Nour, for their love and support.

I owe my every single accomplishment to them.

To my wife Amal and my children Nour, Hussien, and Nada, for their love and support.

TABLE OF CONTENTS

ABSTRACT

Five methods to measure the saturated hydraulic conductivity of Arizona irrigated soils were evaluated using the *in-situ* single ring, double ring, compact constant head permeameter methods, and with tempe cells (soil cores) in the laboratory. Ten Arizona irrigated soils were studied, and the textures of these soils ranged from sand to silty clay. Three water qualities were evaluated, namely the local water, gypsum in local water, and gypsum water (0.005M $CaSO_4 \cdot 2H_2O$ solution). Sites were selected to provide soils having a wide range of soil characteristics and detailed laboratory and field morphology data were measured including soil texture, bulk density, soil aggregation, stickiness, plasticity, moisture retention at various tensions, EC_e, and pH_e.

The results showed that the double ring method was the better *in-situ* method. The relationships between soil properties and K_{sat} were evaluated, and soil properties were examined as predictor variables for K_{sat} in stepwise multiple-regression. Stepwise multiple-regression criteria were set at a probability of F to enter ≤ 0.5 and probability of F to remove ≥ 0.1. Six models are presented that can be used in predicting K_{sat}. Each model has a subset of field and laboratory predictor variables selected based on stepwise multiple-regression criteria, and with some personal judgment. Casewise diagnostics were used to test model performances.

CHAPTER 1

INTRODUCTION

Context of the problem

Hydraulic conductivity (steady state infiltration rates) is the single most important hydraulic parameter for flow and transport-related phenomena in soil. Hydraulic conductivity (K_{sat}) estimates are important in many sciences such as in agronomy and hydrology. In agronomy, soil hydraulic conductivity information is used for irrigation and drainage design, and in irrigation scheduling. Hydrologists use K_{sat} to predict the amount of runoff produced by a given amount of precipitation. It is also important for groundwater recharge. Soil properties like soil texture, bulk density, soil aggregation. and other chemical and physical properties affect hydraulic conductivity. There are different methods used for measuring hydraulic conductivity in the field and a major factor when choosing a field method is the type of flow Bohne et al. (1993). Single and double ring infiltrometers are useful for determining hydraulic conductivity *in-situ* in fields and these devices are simple to use. Disc infiltrometers have become a popular device for measuring *in-situ* hydraulic conductivity (Hussen and Warrick, 1993). Also, the auger hole method which measures change in water level from a flow-measuring reservoir accrues when water enters the soil, and this can be translated into water flux (Amoozegar, 1989). Use of these devices requires an interface of fixed geometry and size. The point source method requires a water flow with a controlled discharge rate applied at fixed points forming a circular interface at the soil surface (Warrick, 1985). As water is applied from a point source, it causes a ponded area to increase until it achieves a maximum size, which then can be considered a steady state. This ponded area is related to water intake and application rate.

Each method has advantages and disadvantages. A major advantage with the auger hole or compact constant head permeameter is that it can measure hydraulic conductivity of the vadose (unsaturated) zone easily and conveniently using an auger hole, and hydraulic conductivity measurements can be conducted at selected depths. Except for this method, all methods are labor intensive for subsoil K_{sat} measurements because they require excavation of the soil to the depth that the K_{sat} measurement will be made. Still, preparation of the borehole can be critical in some soils, such as sandy-textured soils or soils with high gravel content. In particular, the hole wall can collapse after the addition of water.

Measuring techniques for hydraulic properties by many studies have addressed the reliability and usefulness of these different methods under different field conditions (Paige and Hillel, 1993; Gupta et al., 1993; Kanwar et al., 1989; Lee et al., 1985; Mohanty et al. 1991; Mohanty et al., 1994). Mohanty et al. (1994) reported a qualitative comparison among disc permeameter, velocity permeameter, double-tube method, and the constant-head permeameter method; the latter was used in the laboratory. However, the velocity permeameter method took the least net time to achieve steady-state conditions before making the K_{sat} estimation of all the situ methods. In general, the time required in most situ methods, ranges from several hours to almost half a day.

Bathke and Cassel (1991) reported that sand and clay are significantly correlated (statistically) at the 0.01 level with a logarithm of vertical ($\log_{10}$ KV) and horizontal saturated ($\log_{10}$ KH) soil hydraulic conductivity, respectively. Moreover, the most strongly correlated logarithm of the average value of KH and KV was the macroporosity property. Predictive equations for $\log_{10}$ K, $\log_{10}$ KV, and $\log_{10}$ KH were developed by using multiple regression equations. An alternative procedure consists of predicting laboratory measurements from soil bulk density or particle-size distribution (Cosby et al., 1984; Saxton et al., 1986). In this approach, Arya and Paris (1981) have presented different models that described a physical model of soil porosity based on the particle-size distribution. Therefore, a study is necessary to show which soil properties are most effective for hydraulic conductivity. There are still some major problems in estimation of soil hydraulic conductivity by field and laboratory methods or predicting by laboratory measurements of soil bulk density or particle-size distribution.

This dissertation compares the results of four *in-situ* methods and a standard laboratory method. The four *in situ* methods were: (i) single-ring infiltrometer, (ii) double-ring infiltrometer, (iii) compact constant head permeameter, and (iv) disc tension infiltrometer. The laboratory soil cores using the tempe cell as standard laboratory method use on undisturbed soil cores collected from all the ten sites. This study evaluates the relationships between the measurement saturated hydraulic conductivity (steady state infiltration rates), using double ring infiltrometer method and selected soil properties. The intent of this research is to develop new models or refine existing models used by soil scientists to predict the saturated hydraulic conductivity of soils. The specific objectives were:

- Compare results of four different *in-situ* steady state infiltration rates measuring methods and evaluate the methods performance.

- Relate the physical and chemical soil characteristics, measured in the laboratory and in the field by professional soil scientist, to steady state infiltration rates.
- To develop new models or refine existing models to predict the K_{sat} of soils.

Dissertation format

The main body of this dissertation consists of two research papers appended to this dissertation. The evaluation of the methods performance to measure hydraulic conductivity was investigated in the first paper (Appendix A). We concluded the double ring method was the better *in-situ* method in the first paper. Models with subset of predictors were developed in the second paper (Appendix B). The best curve estimations were computed to study the relationships between soil properties estimated in field by soil scientists and K_{sat}. The best curve estimations could then be used in predicting K_{sat} values (cm/hr).

In the first paper, the author designed the field experiment for the first paper, under the guidance of Dr. Donald F. Post. The field and laboratory data were processed in field locations in Tucson and at University of Arizona Maricopa and Yuma Agricultural Centers. Laboratory analyses were completed in Department of Soil, Water and Environmental Science laboratories in Tucson. Soil analyses were also completed by the National Soil Survey Laboratory, Lincoln, NE.

CHAPTER 2

PRESENT STUDY

Summary

The literature review, site descriptions, methods, results, and conclusions of this study are presented in the papers appended to this dissertation. The following is a summary of the most important findings in these papers.

Paper # 1: The saturated hydraulic conductivities (K_{sat}) were measured on five Tucson area soils using the *in-situ* single ring, double ring and compact constant head permeameter methods, and with tempe cells (soil cores) in the laboratory. The soil textures ranged from sandy loam to silty clay loam, and two water qualities were evaluated, the local water and gypsum water (0.005M $CaSO_4 \cdot 2H_2O$ solution).

Single ring is a common method, based on steady state reading for three-dimension flow, and it provides fast results compare to the other *in-situ* methods. Using correction multiplication factors for single ring results did not work efficiently with all soil types. The double ring method provides easy direct measurement, and the results are known immediately because all of the parameters are measured directly over a short time. The compact constant head permeameter "bore hole" technique is not suitable for measurement in the surface zone because over filling the hole can occur. Another limitation is the soil with sandy textures that can easily collapse after addition of water to the hole and result in the enlargement of the hole. The undisturbed soil core samples in the laboratory using tempe cells is based on steady state readings and it measures only the vertical component, and provide fast and easy results in a comfortable laboratory condition. The low conductivity reading of clay soil when undisturbed core soil samples method are used could be due to the swelling of clay soil samples into the limited space of the tempe cell, which causes a collapse of macropores. An opposite behavior could occur for sandy soil samples that fail to maintain their cohesiveness in cores. Water qualities behave differently based on soil textures and soil qualities (e.g. EC and SAR).

Paper # 2: In this study I used the double ring method for obtaining steady-state flow rates of ten soil series measured directly, and three water qualities were used. Two groups of soil properties were evaluated; one group of soil properties were provided by soil scientist estimations made in the field. The other group of soils properties were determined or measured by lab analyses. Hydraulic conductivity of soils can be obtained either by direct measurements or estimated indirectly using soil morphology data. These estimations are often referred to as Pedotransfer functions (Vereecken et al., 1990; Bell and van Keulen, 1995; Batjes, 1996; Lin et al., 1999a,b).

Six new models are proposed to predict hydraulic conductivity of Arizona irrigated soils using either soil properties provided by soil scientists field estimating for models A, B, and C or soils properties determined by lab analysis for models D, E, and F. Model C and model F are restricted to predict hydraulic conductivity of soil texture range from sandy loam to silty clay, as the sand texture was removed from these models.

Soil structure (bulk density, rating bulk density, aggregate stabilities and porosity from volumetric water content) is crucial in determining the hydraulic conductivity behavior in the macropore flow region, whereas texture places major impact on hydraulic conductivity controlled by micropores. Consequently, the classical approach of using only particle-size, bulk density, and organic content is insufficient for predicting hydraulic conductivity. Macroporosity is an integral part of soil structure, which is not reflected by organic C content and bulk density because arid soils have low organic C and soils that shrink and swell are also difficult to evaluate. No single morphological or physical property appears to provide adequate estimation of hydraulic conductivity, and estimation soil hydraulic conductivity requires the use of different combinations of morphological or physical and chemical properties.

Conclusions

The performance of each method depends on different soil morphologic properties, and each K_{sat} measuring method has some limitations. Water qualities behave differentially based on soil textures and soil qualities (e.g. EC and SAR). We concluded the double ring method was the better *in-situ* method.

Six new models (A-F) are proposed to predict hydraulic conductivity of irrigated Arizona soils using either soil properties estimations provided by field soil scientists for models A, B, and C, and soil properties determined or measured by lab analysis for model D, E, and F. Model C and model F are restricted to predict hydraulic conductivity of soil texture range from sandy loam and silty clay. The suggested models in this study are limited to the observed samples. The six empirical models ensured their best performance for quick and economic estimations of necessary model input parameters, particularly for regional-scale of irrigated soils studied.

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APPENDIX A:

AN EVALUATION OF METHODS TO MEASURE THE SATURATED HYDRAULIC CONDUCTIVITY OF SOILS

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AN EVALUATION OF METHODS TO MEASURE THE SATURATED HYDRAULIC CONDUCTIVITY OF SOILS

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ABSTRACT

The saturated hydraulic conductivity (K_{sat}) was measured on five Tucson Basin soils using the *in-situ* single ring, double ring and compact constant head permeameter methods, and with tempe cells (soil cores) in the laboratory. The soil textures ranged from sandy loam to silty clay loam, and two water qualities were evaluated, the local water and gypsum water (0.005M $CaSO_4 \cdot 2H_2O$ solution). Three *in-situ* replications were completed on each soil using the two water qualities. The mean intake K_{sat} measurements for the five soils (15 measurements for each water quality) were 2.4 and 2.2, 1.0 and 0.9, 2.0 and 1.6, and 1.2 and 1.2 cm/hr for the single ring, corrected single ring, double ring, and the compact constant head permeameter, respectively, and 2.4 cm/hr for the lab cores. The mean values appear to be comparable for some methods; however, there were significant differences between soils, and water quality also affected the measured K_{sat}. We concluded the double ring method was the better *in-situ* method, because the results were closer to the mean of all measurements, and they generally agreed with K_{sat} predictions of professional soil scientists, and with experimental results obtained for similar soils. Statistical analyses of the results showed there were interactions between soil, water and the method of measuring K_{sat}, and results varied among the soils. Interpretations of experimental results should consider all factors and how they interact when measuring or predicting the K_{sat} of soils.

INTRODUCTION

The saturated hydraulic conductivity (K_{sat}), sometimes referred to as the steady state infiltration rate of soil, is the single most important hydraulic parameter for flow and transport-related occurrences in soil. Many soil properties affect K_{sat}, particularly soil texture and the bulk density, soil porosity characteristics of the soil. Soil structure affects K_{sat} because it affects soil porosity. Also chemical properties such as the sodium absorption ratio are important too.

There are many methods used for measuring hydraulic conductivity in the field. A major factor when choosing a field method is the type of flow. Bohne et al. (1993) points out that infiltration is a wetting process, and single and double ring infiltrometers are useful for determining hydraulic conductivity *in-situ*. These devices are simple to use in the field. The disc infiltrometer has become a popular device for measuring *in-situ* hydraulic conductivity (Hussen and Warrick, 1993). In the case of the disc infiltrometer, the measurable change in water level from a flow-measuring reservoir occurs when water enters the soil, which can be translated into water flux.

A major advantage with the compact constant head permeameter (sometimes called a borehole permeameter) is that it can measure hydraulic conductivity of the vadose (unsaturated) zone easily and conveniently by using an auger hole, and hydraulic conductivity measurements can be conducted at different soil depths (Amoozegar, 1989). Except for the compact constant head permeameter method, all methods are labor intensive for subsoil K_{sat} measurements, because they require excavation of the soil to the depth that the K_{sat} measurement will be made. Still, preparation of the borehole can be critical in sandy soils or soils with high gravel content, because the hole may collapse after the addition of water.

The objectives of this research were to compare the K_{sat} of five soils using four *in-situ* methods and a standard soil-core laboratory method. The four *in-situ* methods were (i) single ring infiltrometer, (ii) double ring infiltrometer, (iii) compact constant head permeameter and (iv) disc tension infiltrometer, plus the laboratory soil cores using the tempe cell. A description of these methods follows.

MATERIALS AND METHODS—DESCRIPTION OF K_{sat} METHODS

Five soils (Pima, Grabe, Gila, Anthony, and Vinton) were selected in Tucson, AZ for making *in-situ* measurements of K_{sat}. Field pedon descriptions were prepared and samples collected for laboratory analyses. All soils are classified at the Subgroup level as Typic Torrifluvents; the Gila, Anthony and Grabe soils family classification is "coarse-loamy, mixed, superactive, calcareous, thermic"; the Pima is "fine-silty, mixed, superactive, calcareous, thermic"; and the Vinton is "sandy, mixed, superactive, thermic". Table 1 includes soil characterization data for these soils.

The surface soil at four sites (Gila, Vinton, Grabe, and Anthony) were excavated to a depth of 20 cm and Pima was excavated 30 cm, where the single and double-ring infiltrometers measurements were made. These soils were excavated because K_{sat} measurements, using the compact constant head permeameter, are made 20^{+} cm below the soil surface. A 3 x 2 m plot was divided into 6 equal 1 x 1 m subplots. Within each subplot three replications of *in-situ* methods were made. Two soil cores and soil samples were collected from the plot for characterization in the laboratory.

Two water qualities were used; the local water was the on-site source and the electrical conductivity (EC) ranged from 0.22 to 0.57 dSm^{-1} and sodium absorption ratio (SAR) ranged from 1.1 to 4.5%. The gypsum water (0.005M $CaSO_4 \cdot 2H_2O$ solution) was made by mixing 0.86 gram per liter to deionized water, which gave an EC of 0.68 dSm^{-1}.

Single Ring (SR)

Bouwer (1986) describes single-ring infiltrometers in detail. We used a 30 cm in diameter single-ring cylinder (infiltrometer) which was lightly pushed or gently driven approximately 5 cm into the soil with as little disturbance of soil as possible. The soil surfaces were left in their natural condition and only rocks, woody stems, or other items were removed. Before inserting the cylinder the plot was flooded using local water, one day in advance in sandy or "soft" soil, or two days in advance in clay or "hard" soils. A constant head of water was maintained in the infiltrometer with a Mariotte-syphon arrangement as explained in Bouwer (1986). The soil surface was covered with a towel to minimize surface disturbance when solutions were applied. Measurements were taken after the steady state infiltration rates were reached and the results were recorded by using the falling-head method. The height of ponded water was measured to the nearest millimeter. Other researchers (Buttle and House, 1997, Tayor et al., 1991, and Prieksat et al., 1992) have also used the single-ring infiltrometers, and provide additional experimental results describing this method.

Corrected Single-Ring (CSR)

Reynolds and Elrick (1990) reported that correction factors should be used to adjust steady state infiltration rate readings of single-ring to "adjust" for the one dimensional-flow condition. They report that shape (correction) factors are dependent on various combinations of depth of ponding, depth of ring insertion, ring radius and soil textures. These authors grouped all soils into three classes, namely clay, loam, and sand. We used their factors to correct our single ring data as follows: Pima silty clay loam soil was 0.417 and Grabe loam and Gila, Anthony, and Vinton fine sandy loam soils were 0.405.

Double-Ring (DR)

The double-ring infiltrometer measurements were taken after the steady state infiltration rates were reached in the single-ring infiltrometer measurements. The single-ring cylinder was left in place, and a second 10 cm cylinder was lightly pushed or gently driven by hand approximately 5 cm into the soil. This task was easy to accomplish because the soils were saturated, so disturbance of the soil was minimal. The water head was kept the same in the external ring during the recording of steady state infiltration rates in the internal ring using the falling-head method. The height of ponded water was measured to the nearest millimeter. Other researchers (Fattah and Upadhyaya, 1996, Kumke and Mullins, 1997, Sakai et al., 1992, and Ashraf et al., 1997) also used the double-ring infiltrometer and additional information on this method is included in their papers.

Compact Constant Head Permeameter (CCHP)

Amoozegar (1989) describes the Compact Constant Head Permeameter in detail. This method uses an auger "borehole" that creates a 6-cm in diameter hole, and the hydraulic conductivity measurements were conducted at a selected depth (below 20 to 30 cm in this research). For a 6-cm diameter hole, a minimum of 15-cm depth of water in the hole is required, and after determining the three consecutive steady-state flow rates, the height of water level in the flow-measuring reservoir was measured to the nearest millimeter. The depth of water in the hole was measured and recorded precisely. At this point, field data collection is completed. One of the available equations used for calculating K_{sat} is the Glover solution (Amoozegar, 1992). Katul et al. (1997) and Polad (1995) have also used the CCHP and present additional information about this procedure.

Disc Tension Infiltrometer (DTI)

The disc tension infiltrometer procedure we used is described in Hussen and Warrick (1995). The disc tension infiltrometer uses a 20-cm diameter disc, which was allowed to soak in water for at least 12 hours prior to conducting the experiment. Three tensions (15, 10, and 6 cm) were applied on the disc infiltrometer and the steady state water absorption by the soils were measured. The best fit of K_{sat} and were found from Wooding's equation using steady state flow at different tensions (Wooding, 1968), where K_{sat} is saturated hydraulic conductivity, and a constant equivalent to λ_c^{1}. Nonlinear optimization fitting procedures were used which minimized the mean square error between provided data and Wooding's equations as explained in Hussen and Warrick, (1993). Lin et al., 1999 also used the disc tension infiltrometer.

Tempe Cell (TC)

The falling-head method in the tempe cell was used for soil core measurements as described by Klute and Dirksen (1986). The core was 5.3-cm in diameter and the height was

3.0-cm, and the soil was retained on a nylon mesh base, which was placed a whatman No. 42 filter paper. A filter paper was also placed on the soil surface to protect it from disturbance. The columns were then wetted under capillary action from below using gypsum water. The steady-state flow rate was corrected for temperature as explained in Klute and Dirksen (1986). Southard and Buol (1988), Franzmeier (1991), and Mohanty et al., (1998) are other researchers who used this method and presented experimental results related to this method.

Al-Jabri (1995) conducted the disc tension infiltrometer data on the Gila and Pima soils. The sample sites were the same; however, his data was collected in fall of 1995 and our data in spring of 1998.

RESULTS AND DISCUSSION

Table 1 lists the soil texture, bulk density, carbonates (CO_3^-), electrical conductivity (EC_e) (1:1) extracted and sodium absorption ratio (SAR) extracted from a soil paste for the five soils evaluated in this study. The soils ranged from the Pima silty clay loam (33% clay, 18% sand) to the Vinton fine sandy loam (7% clay, 72% sand). Three of the five soils were classified as having fine sandy loam textures; however the percentages of clay and sand were quite different. The bulk densities for these soils were all medium to high (Soil Survey Staff 1993, p. 109), because of past compaction by tillage equipment used at these sample sites. The structure was also massive for all soils, which contributed to the high bulk density and likely affected the K_{sat} of each soil.

The mean, standard deviation (S.D.), and coefficient of variation (CV) for the saturated hydraulic conductivities for the five soils using all methods are summarized in Table 2.

Comparisons among *In-situ* Methods with both Local Water and Gypsum Water

A split-plot experiment was conducted in a completely randomized design with whole-plot treatments as 5 × 2 factorial, where factor one is soil types with five levels (Pima, Grabe, Gila, Anthony, and Vinton) and factor two is water types with two levels (local water and gypsum water), and the subplot treatments as four levels (single ring, corrected single ring, double ring and compact constant head permeameter methods) of factor three. There were three replications and all treatment effects were fixed. The output analysis of Mixed Procedure using "PROC MIXED" code for this part was generated using [SAS/STAT] software, Version [6.11] of the SAS System for [Unix]. Copyright [1999] SAS Institute Inc.

was used to compute the analysis of variance of the split-plot design. The pairways comparison test was used to examine the means, and this test compares the differences of Least Squares Means among the methods.

Statistical analyses of the experimental results shows significant differences for the soil and method main effects with P-values equal to 0.0001, but the water quality main effects shows no significant differences with P-values equal to 0.1467. On the other hand, the two-factor interaction (soil x water) and (soil x method) are significant with P-value equal to 0.0036 and 0.0001, respectively. The significance of the three-factor interaction (soil x water x method), with P-values equal to 0.0123, indicates that soil, water, and method are interrelated in their effect on the hydraulic conductivity. The presence of interaction among soil, water and method factors suggest that the interpretations should not be based on main affects only, as the factors do not act independently and interpretations should not be based on simple affect contrasts.

Table 3 shows differences among methods were statistically significant for hydraulic conductivity means with the two water qualities for the Pima soil. Generally, the three methods, single ring, corrected single ring, and double rings using gypsum water showed improved of conductivities over the three methods using local water. This could be due to improved aggregate stability of Pima soil by the gypsum amendment. There were six treatment combinations of significant differences between the methods at a confidence level of 95%. There were significant differences between the SR-LW versus DR-LW, CCHP-LW, SR-GW, and CCHP-GW methods; there were significant differences between the SR-GW versus CSR-GW, DR-GW, and CCHP-GW methods; there were significant differences between CSR-LW and SR-GW methods; there were significant differences between CSR-GW and CCHP-GW methods; there were significant differences between DR-LW and SR-GW methods; and there were significant differences between CCHP-LW and SR-GW methods. All treatment combinations were expected to have significant differences when compared to the single ring methods with no correction factor to adjust to one dimension flow. The double ring methods using gypsum water averaged 52% higher conductivities than the double ring methods using local water. This may be due to improved aggregate stability of Pima soil by gypsum amendment.

The pairways comparison test was used to examine the result method means of Grabe soil. The test showed no significant differences between all methods (Table 3). The Grabe soil seemed to be more stable than the sandier Gila, Anthony, and Vinton soils, it had lower clay content than the Pima soil, and there was some weak structure. Perhaps for these reasons the Grabe soil was more stable and all methods gave similar results.

There were significant differences among methods for hydraulic conductivity with two water qualities for the Gila soil. There were two treatment combinations of significant differences between the methods at a confidence level of 95%. The differences were between the SR-LW versus CSR-LW, CCHP-LW, SR-GW, CSR-GW, DR-GW, and CCHP-GW methods; and between DR-LW and CSR-GW methods. The single ring using gypsum water averaged 58% lower conductivities than the single ring using local water. This reverse behavior could be due to a change of water qualities. Leaching Na^{+} to subsoil after replacing exchangeable Na^{+} by Ca^{++} may cause infiltration reduction as in the early stage of soil reclamation. Robbins (1986) hypothesized the hydraulic conductivity reduction occurred as the gypsum dissolves and begins to replace exchangeable Na^{+} cation at greater depths, which may not maintained the required threshold electrolyte concentration levels in lower soil layers, which can cause subsoil clay dispersion.

The single ring using local water averaged 60% higher conductivities for the Gila soil than corrected single ring using local water. We expected significant difference because the last was the result of multiplication by the correction factor to adjust to one dimension flow. It seems that the correction factor worked well with single ring to adjust to one dimension flow for the Gila soil, because there were no significant differences between CSR-LW and DR-LW methods and between CSR-GW and DR-GW methods. The results show no significant differences between the mean readings for double rings and compact constant head permeameter using two water qualities for the Gila soil.

Table 3 presents the results among all methods used on Anthony soil. There were no significant differences between the double ring methods using local water or using gypsum water and between the compact constant head permeameter methods using local water or using gypsum water. There were six treatment combinations of significant differences between the methods at a confidence level of 95%. The differences were between the SR-LW versus CSR-LW and CCHP-LW methods; between the SR-GW versus CSR-GW and CCHP-GW methods; significant differences between the CSR-LW versus SR-GW and DR-GW methods; significant differences between CSR-GW and DR-GW methods; significant differences between DR-LW versus SR-GW methods; and there were significant differences between the CCHP-LW versus SR-GW and DR-GW methods.

For the Anthony soils the DR-LW method averaged 40% higher conductivities than the CSR-LW method, and the DR-GW averaged 48% higher conductivities than the CSR-GW method, and the DR-GW averaged 33% higher conductivities than the DR-LW method.

For the Vinton soil there were no significant differences between the CSR-LW versus CSR-GW and CCHP-GW methods and between CCHP-LW and CCHP-GW methods. Table 3 shows there were seven treatment combinations of significant differences between the methods at a confidence level of 95%. There were significant differences between single ring methods, which were adjusted to one dimension flow by a multiplication correction factor, and double ring methods. The DR-LW method averaged 56% higher conductivities than the CSR-LW method. And the DR-GW method averaged 50% higher conductivities than the CSR-GW method. These results concluded that correction multiplication factor did not work efficiently for the Vinton soil. On the other hand, there were significant differences between double ring methods and compact constant head permeameter methods. The DR-LW method averaged 42% higher conductivities than the CCHP-LW method. And the DR-GW method averaged 22% higher conductivities than the CCHP-GW method. The enlargement of the hole and the collapse of the bottom auger hole wall were observed after addition of water due to the condition. To minimize collapse of the hole wall, inserting a section of commercially available two inch in diameter PVC well screen in the hole was recommended by the manufacture for sandy soils to eliminate soil slumping. Moreover, gopher holes were observed into the subsoil of Vinton soil, and this could explain the very significant differences among all methods.

Comparisons Among *In-Situ* Methods and Soil Cores Using Gypsum Water

A split-plot experiment was conducted in a completely randomized design where factor one is soil types used as whole-plot treatments with five levels of the five soil types used, and the subplot treatments with four levels of factor two of the four methods used. There were three replications for *in-situ* methods, but two replications for soil cores method. All treatment effects were fixed. The output analysis of Mixed Procedure using "PROC MIXED" code for this part was generated using [SAS/STAT] software, Version [6.11] of the SAS System for [Unix]. Copyright [1999] SAS Institute Inc. was used to compute the analysis of variance of the split-plot design. The pairways comparison test was used to examine the means, and this test compares the differences of Least Squares Means among the methods.

An analysis of variance was applied to compare calculated hydraulic conductivity on Gila, Pima, Vinton, Grabe, and Anthony using SR, CSR, DR, CCHP, and TC methods with only gypsum water and showed significant differences for the soil and method main effects with p-value equal to 0.0001. Also the two-factor interaction (soil * method) is significant with p-value equal to 0.0012. The presence of interaction between soil and method factors suggests that the interpretations should be based on simple effect contrasts.

Table 4 shows there was one treatment combination of significant differences between the methods at a confidence level of 95%, and that was between the SR versus CCHP and TC methods for Pima soil. The undisturbed soil core samples (tempe cell) averaged 89% lower conductivities than the double rings. This reduction could be due to a swelling of Pima soil samples (heavy soil texture) into the limited space of temp cell, which causes a collapse of macropores of the soil and subsequently leads to low conductivity. There were no significant differences between SR versus CSR and DR methods; and CSR, DR, CCHP, and TC methods.

The pairways comparison test was used to examine the result method means for Grabe soil. The test showed no significant differences between all methods (Table 4).

The data for Gila soil (Table 4) shows significant differences among methods for hydraulic conductivity using gypsum water. There were no significant differences between the SR versus CSR, DR, and CCHP methods; the CSR versus DR and CCHP methods; and the DR and CCHP methods. The only significant difference was between the mean of methods TC and the other methods. This could be due to the limitation of *in-situ* methods that cannot be directly used to determine K_{sat} of a relatively thin (e.g., 10 cm thick) layer or horizon. Generally, the measured K_{sat} by those techniques represents overall saturated hydraulic conductivity of the soil around the wetted perimeter. The undisturbed soil core samples (tempe cell) averaged 75, 90, 83, and 72% higher conductivities than the single ring, corrected single ring, double ring, and the compact constant head permeameter, respectively.

There was one significant difference between SR and TC for the Anthony soil. The undisturbed soil core samples (tempe cell) averaged 72% lower conductivities than the single ring.

The Vinton soil showed no significant differences between the SR versus DR and TC methods; or DR and CCHP methods. Table 4 shows there were four treatment combinations of significant differences between the methods at a confidence level of 95%: SR versus CSR, and CCHP methods; the CSR versus DR, CCHP and TC methods; the DR and TC methods;

and between the CCHP and TC methods. The undisturbed soil core samples (tempe cell) averaged 67, 34, and 48% higher conductivities than the corrected single ring, double ring, and the compact constant head permeameter, respectively. This higher reading of undisturbed soil core method could be due to sandy texture samples that fail to maintain their cohesiveness in cores.

Comparisons of Disc Tensiometer Infiltrometer to Other *In-Situ* Methods for Gila and Pima Soils

One-way analysis of variance was applied to compare calculated hydraulic conductivity for the Gila and the Pima soils separately using SR, CSR, DR, CCHP, and DTI methods with local water to test the method effects on the hydraulic conductivity. Five methods were used with three replicate plots in a completely randomized design. The output analysis of general liner model Procedure using "PROC GLM" code for this part was generated using [SAS/STAT] software, Version [6.11] of the SAS System for [Unix]. Copyright [1999] SAS Institute Inc. was used to compute the analysis of variance of a completely randomized design. Table 2 presents the results of these studies. Analyzing of experiments of Gila and Pima soils shows significant differences for the method main effect with P-value 0.007 and 0.0001 respectively.

For the Pima soil, the disc tension infiltrometer averaged 5% lower conductivities than the corrected single ring, but 23 and 77% higher conductivities than double ring, and the compact constant head permeameter, respectively. The disc tension infiltrometer on Gila averaged 55, 24, and 39% higher conductivities than the corrected single ring, double ring, and the compact constant head permeameter, respectively. The results of the differences of least squares means among the methods shows that there were no significant differences between methods of double rings and disc tension infiltrometer for both Gila and Pima soils.

CONCLUSIONS

Single ring is a common method, based on steady state reading for three-dimension flow, provides fast results compare to the other *in-situ* methods. Using correction multiplication factors for the result of single ring may not work efficiently with all soil types. The double ring method provides easy direct measurement, and the results are known immediately because all of the parameters are measured directly over a short time. The compact constant head permeameter technique is not suitable for measurement in the surface zone because the high possibility of over filling the hole occur when the flow rate should decline with time. Another limitation is soil with sandy textures can easily collapse after addition of water to the hole and result in the enlargement of the hole. The disc tension infiltrometer requires steady state flow for three or more tensions at the same measurement site, from which a best fitting method is used to find the hydraulic conductivity. Multiple measurements without moving the disc infiltrometer are recommended to avoid possible spatial variation differences between the tensions. The undisturbed soil core samples in the laboratory using tempe cell, based on steady state readings and measured only the vertical component, provides fast and easy results at the comfortable laboratory condition. The low conductivity reading of clay soil when undisturbed core soil samples method are used, could be due to a swelling of clay soil samples into the limited space of tempe cell, which causes a collapse of macropores. An opposite behavior could occur for sandy soil samples that fail to maintain their cohesiveness in cores. Water qualities behave differentially based on soil textures and soil qualities (e.g. EC and SAR). Each method performance depends on the soil texture and structure, and each K_{sat} measuring method has some limitations. We concluded the double ring method was the better *in-situ* method.

Table 1. Soil characterization data for the five soils.

Soil Series	Depth (cm)	Textural Class	% Clay	% Sand	Bulk Density (g/cm^3)	% CO^-_3	ECe (dSm^{-1}) 1:1	% SAR
Pima	0-30	Silty clay loam	33	17		10	0.44	
	30-60	Silty clay loam	33	19	1.74	9	0.36	6.6
Grabe	0-18	Loam	24	37		4	0.34	
	18-45	Loam	19	45	1.54	6	0.34	7.5
Gila	0-16	Fine sandy loam	10	56		4	0.29	
	16-42	Fine sandy loam	9	55	1.44	5	0.29	3.4
Anthony	0-24	Fine sandy loam	13	57		3	0.21	
	24-50	Fine sandy loam	10	65	1.46	3	0.19	6.1
Vinton	0-17	Fine sandy loam	7	72		2	0.29	
	17-71	Fine sandy loam	7	69	1.53	2	0.29	6.6

Table 2. Saturated hydraulic conductivity means, standard deviation (SD), and coefficient of variation percentage (CV%) for the five soils using the different measurement methods.

	SR-LW	CSR-LW	DR-LW	CCHP-LW	DTI-LW*	SR-GW	CSR-GW	DR-GW	CCHP-GW	TC-GW
Pima silty clay loam										
Mean	0.88	0.37	0.27	0.08	0.35	1.67	0.70	0.56	0.07	0.06
S.D.	0.13	0.06	0.12	0.04	0.09	0.63	0.26	0.15	0.06	0.00
CV%	14	15	47	50	25	38	38	27	82	0
Grabe loam										
Mean	0.73	0.29	0.53	0.47	NA	0.63	0.25	0.42	0.59	1.48
S.D.	0.34	0.13	0.37	0.07	NA	0.09	0.04	0.01	0.12	0.01
CV%	46	45	69	15	NA	14	14	2	20	1
Gila fine sandy loam										
Mean	1.60	0.65	1.11	0.89	1.46	0.67	0.27	0.47	0.76	2.70
S.D.	0.30	0.12	0.10	0.47	0.10	0.26	0.10	0.24	0.56	0.52
CV%	19	19	9	53	7	38	39	51	74	19
Anthony fine sandy loam										
Mean	1.57	0.64	1.07	0.58	NA	2.04	0.83	1.59	1.04	0.57
S.D.	0.47	0.19	0.29	0.16	NA	1.01	0.41	0.94	0.08	0.52
CV%	30	30	27	28	NA	50	50	59	8	92
Vinton fine sandy loam										
Mean	7.41	3.00	6.82	3.97	NA	5.80	2.35	4.73	3.71	7.15
S.D.	1.01	0.41	1.46	0.83	NA	0.29	0.11	0.31	0.19	4.70
CV%	14	14	21	21	NA	5	5	7	5	66
Overall Mean—All Soils										
Mean	2.44	0.99	1.96	1.20		2.17	0.87	1.55	1.23	2.39
S.D.	0.45	0.18	0.47	0.31		0.58	0.19	0.33	0.20	1.15
CV%	25	24	35	33		30	30	29	38	36

* Al-Jabri (Master thesis, 1995)

NA Not Available.

SR-LW and GW: Single Ring-Local and Gypsum Water
CSR-LW and GW: Corrected Single Ring-Local and Gypsum Water
DR-LW and GW: Double Ring-Local and Gypsum Water
CCHP-LW and GW: Compact Constant Head Permeameter-Local and Gypsum Water
DTI-LW: Disc Tensiometer Infiltrometer-Local Water
TC-GW: Tempe Cell-Gypsum Water

Table 3. Comparison of the differences of least squares means among the *in-situ* methods for the five soils using local and gypsum waters.

Method	Pima	Grabe	Gila	Anthony	Vinton
SR-LW vs. CSR-LW	NS	NS	**	**	**
SR-LW vs. DR-LW	*	NS	NS	NS	*
SR-LW vs. CCHP-LW	**	NS	*	**	**
SR-LW vs. SR-GW	*	NS	*	NS	**
SR-LW vs. CSR-GW	NS	NS	**	NS	**
SR-LW vs. DR-GW	NS	NS	**	NS	**
SR-LW vs. CCHP-GW	*	NS	*	NS	**
SR-GW vs. CSR-GW	**	NS	NS	**	**
SR-GW vs. DR-GW	**	NS	NS	NS	**
SR-GW vs. CCHP-GW	**	NS	NS	**	**
CSR-LW vs. DR-LW	NS	NS	NS	NS	**
CSR-LW vs. CCHP-LW	NS	NS	NS	NS	**
CSR-LW vs. SR-GW	**	NS	NS	**	**
CSR-LW vs. CSR-GW	NS	NS	NS	NS	NS
CSR-LW vs. DR-GW	NS	NS	NS	*	**
CSR-LW vs. CCHP-GW	NS	NS	NS	NS	NS
CSR-GW vs. DR-GW	NS	NS	NS	**	**
CSR-GW vs. CCHP-GW	*	NS	NS	NS	**
DR-LW vs. CCHP-LW	NS	NS	NS	NS	**
DR-LW vs. SR-GW	**	NS	NS	*	**
DR-LW vs. CSR-GW	NS	NS	*	NS	**
DR-LW vs. DR-GW	NS	NS	NS	NS	**
DR-LW vs. CCHP-GW	NS	NS	NS	NS	**
DR-GW vs. CCHP-GW	NS	NS	NS	NS	**
CCHP-LW vs. SR-GW	**	NS	NS	**	**
CCHP-LW vs. CSR-GW	NS	NS	NS	NS	**
CCHP-LW vs. DR-GW	NS	NS	NS	**	*
CCHP-LW vs. CCHP-GW	NS	NS	NS	NS	NS

NS Not significantly different.
* Significantly different at the 95% confidence level.
** Significantly different at the 99% confidence level.

SR-LW and GW: Single Ring-Local and Gypsum Water
CSR-LW and GW: Corrected Single Ring-Local and Gypsum Water
DR-LW and GW: Double Ring-Local and Gypsum Water
CCHP-LW and GW: Compact Constant Head Permeameter-Local and Gypsum Water

Table 4. Comparison of differences of least square means among the *in-situ* methods and laboratory cores using gypsum water.

Method	Pima	Grabe	Gila	Anthony	Vinton
SR vs. CSR	NS	NS	NS	NS	**
SR vs. DR	NS	NS	NS	NS	NS
SR vs. CCHP	*	NS	NS	NS	**
SR vs. TC	*	NS	**	*	NS
CSR vs. DR	NS	NS	NS	NS	**
CSR vs. CCHP	NS	NS	NS	NS	*
CSR vs. TC	NS	NS	**	NS	**
DR vs. CCHP	NS	NS	NS	NS	NS
DR vs. TC	NS	NS	**	NS	**
CCHP vs. TC	NS	NS	*	NS	**

NS Not significantly different.
* Significantly different at the 95% confidence level.
** Significantly different at the 99% confidence level.

SR: Single Ring
CSR: Corrected Single Ring
DR: Double Ring
CCHP: Compact Constant Head Permeameter
TC: Tempe Cell

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APPENDIX B:

Predicting Steady State Infiltrations Rates for Arizona Irrigated Soils

Mohammed H. Bagour
Donald F. Post

ABSTRACT

The objective of this research is to evaluate and perhaps refine existing models used to predict K_{sat} by using selected field morphology data including particle size distribution, stickiness, plasticity, bulk densities, and soil aggregation estimations made by field soil scientists with lab analyses. Laboratory analyses include particle size distribution, bulk densities, soil aggregation-structure, soil moisture release curve data, and the electrical conductivity (EC) and sodium absorption ratio (SAR) chemical properties of the soils and the water. The K_{sat} of ten soils were determined using the double ring infiltrometer, and these measurements were regressed against field morphology properties and laboratory analyses. The soil textures ranged from sand to silty clay, and three water qualities were evaluated, namely local water, gypsum in local water and gypsum water (0.005M $CaSO_4 \cdot 2H_2O$ solution).

Multiple linear regression models were developed to predict the saturated hydraulic conductivity of soils using these data. Six models are presented that could be used in predicting K_{sat}. Each model has a subset of multiple predictor variables selected based on stepwise multiple-regression criteria and using some personal judgment. Casewise diagnostics was used to test model performances. Based on the statistical evaluation criteria, the models performed well, and gave a satisfactory validation versus the field measured data.

INTRODUCTION

The saturated hydraulic conductivity (K_{sat}), sometimes referred to as the steady state infiltration rate of soil, is the single most important hydraulic parameter for flow and transport-related phenomena in soil. Measuring saturated hydraulic conductivity is expensive, time consuming, labor intensive and relatively cumbersome. Additionally, field soils exhibit large spatial variabilities in their hydrologic properties, especially their hydraulic conductivities. This variability implies that a large number of field measurements can be required to characterize a given field or an area. There are many physical soil properties that affect hydraulic conductivity, such as soil texture, soil structure, bulk density and chemical properties like the EC and SAR of the soil and water.

The relationships between K_{sat} and soil properties have been reported in many investigations. Mason et al. (1957) found that hydraulic conductivity was positively and consistently correlated with the percentage of pores that drained at 60 cm H_2O (6.0 kPa) pressure. He further reported that bulk density was not a reliable predictor of hydraulic conductivity. Bouma and Anderson (1973) found the predicted K_{sat} values from an assessment of the nature of planar voids between structural units agree reasonably well with *in situ* K_{sat} measurements. Other researchers report empirical equations using measurable soil characteristics such as particle size distribution, bulk density, effective porosity, and carbon content can be developed to predict soil hydraulic properties (Gupta and Larson, 1979; Bloemen, 1980; Arya and Paris, 1981; Rawls et al., 1982; Rawls, 1983; Puckett et al., 1985; Haverkamp and Parlange, 1986; Wosten and Van Venuchten, 1988; Ahuja et al., 1989; Vereecken et al., 1989; Wu et al., 1990; Franzmeier, 1991; Jabro, 1992). Tyler and

Wheatcraft (1989, 1990) have described models of soil that relate particle-size distribution to pore-size distribution, and thus to soil water properties. Cosby et al., (1984) and Saxton et al., (1986) developed an alternative procedure for predicting soil water properties from simple routine laboratory measurements of soil bulk density and particle-size distribution.

Franzmeier (1991) proposed a model by which K_{sat} can be estimated from effective porosity (Φ_e), the difference between total porosity and the volumetric soil water content at 33 kPa of suction. The saturated hydraulic conductivity of weathered granitic bedrock and overlying soils was determined and related to the regolith morphology and porosity (Graham et al., 1997). Lin et al. (1999a) proposed a morphology quantification system that examined basic relationships between five major soil morphological features (texture, initial moisture, pedality, Macroporosity, and root density) and steady infiltration rates for 96 soil horizons of varying structure. Based on these relationships, a point scale system was developed as an approach to quantify soil morphology. Lin et al. (1999b) further showed that soil hydraulic properties could be estimated from morphological features determined in situ (including texture, initial moisture, pedality, macroporosity, and root density), also through a morphology quantification system.

In general, infiltration rates and hydraulic conductivities decrease with increasing Sodium Absorption Ratio (SAR) and decreasing Electrical Conductivity (EC) of irrigation water (Oster, 1994). Chemical dispersion and movement of clay particles occurs and plug the conducting pores. In practice, accumulation of salt-water irrigation increase after saline water is applied to the soil, and the ESP of the surface soil equilibrates with the SAR of the irrigation water. Oster (1994) indicated that as evaporation concentrates the soil water, the

EC and SAR of the irrigation water and the ESP of the soil increase. Irrigation with non-saline water or rainfall tends to rapidly reduce the EC of the soil water near the soil surface. The ESP, on the other hand, will not be reduced as much. McNeal and Coleman (1966) report the typical effects of a combination of salt concentration and exchangeable sodium on the hydraulic conductivity of soils from the western United States. Each soil responds differently to the same combination of salinity and SAR because of differences in clay, mineralogy, iron oxide, aluminum oxide, and organic matter content. Severe chemical dispersion increase when electrolyte concentration decreases below the critical flocculation concentration (CFC) at which clay minerals flocculate (Shainberg and Letey, 1984; Goldberg and Forster, 1990). Rainfall can cause electrolyte concentration to fall below the CFC, resulting in enhanced dispersion and severe reduction infiltration in irrigated arid regions as well as under humid, rain fed conditions (Sumner, 1993). Similar conditions occur where low electrolyte concentration irrigation waters (~0.10 dSm^{-1}) are used for irrigation (Doneen, 1948).

Oster and Singer (1984) pointed out that in California soil, where soil textures range from sandy loams to clay loams, even when the ESP percent is low (<5), problems of infiltration reduction are usually related to the use of non-saline water for irrigation. Clay swelling and dispersion are two mechanisms that account for changes in hydraulic properties and soil structure (Quirk, 1986). In general, arid and semiarid soils are characterized by poor aggregate stability and crust formation at the surface (Shainberg and Letey, 1984). Swelling reduces the radii of soil pores while dispersion after breakdown or slaking (Abu-Sharar et al., 1987), and subsequent clay movement leads to blockage of soil pores (Frenkel et al., 1978).

Both swelling and dispersion reduce the saturated and unsaturated hydraulic conductivities of the soil (McNeal et al., 1966; Rengasamy et al., 1984). Hydraulic conductivity decreased with decreasing electrolyte concentration, especially at higher SAR levels. Subsequently, the major cause for such reductions was due to aggregate slaking rather than to clay dispersion, migration and clogging of conducting pores (Abu-Sharar and Salameh, 1995).

Quirk and Schofield (1955) introduced the concept of threshold electrolyte concentration (TEC). This concept is the salinity or electrolyte concentration of soil solution at which a 10-15% decrease in saturated hydraulic conductivity occurred for a silt loam soil. A common practice is to add gypsum to the soil surface or to irrigation water to maintain infiltration. Gypsum begins to replace exchangeable Na at greater depths when reclamation approaches completion with the amended soil layer. Decreased hydraulic conductivity of the second phase of reclamation was the result of retained sodium at greater depth (Robbins 1986).

Electrolyte concentrations may not be adequate to meet TEC requirements for hydraulic conductivity for calcareous soils during irrigation with low-salinity irrigation waters, or after extensive rainfall unless the partial pressure of carbon dioxide is enhanced by cropping (Robbins, 1986) or the soil contains significant levels of Mg (Alperovitch et al. 1981). In addition, irrigation water must contain sufficient Cl and SO_4 salts to compensate the TEC requirements for infiltration in soil solutions where SAR near the surface exceeds 5. For soils with gypsum, minimum electrolyte concentrations may not meet TEC requirements for hydraulic conductivity, but possibly not for infiltration. Electrolyte concentrations at the surface will strongly correlate with the soil gypsum content, quantity of gypsum amendment added to the surface, gypsum dissolution kinetics (Oster, 1982), and Cl salts found in the irrigation water. ESP values from 2 to 5, with low solution concentration values cause hydraulic conductivity to decrease by 25% or even more (Crescimanno et al. 1995).

MATERIALS AND METHODS

Ten irrigated Arizona soils having a wide range of soil characteristics were selected for in situ measurements of each soil's saturated hydraulic conductivity (K_{sat}). Table 1 lists the soil series, texture of the Ap horizon, taxonomic classification, and sample location for each soil. A 3 x 2 m plot was divided into six (6) equal 1 x 1 m subplots as shown in Figures 1 and 2. The double-ring infiltrometer was placed in each subplot to make the in situ measurements. The surface soil of the Gila, Vinton, Grabe, and Anthony soils were excavated to a depth of 20 cm, and the Pima soil was excavated to a 30 cm depth, where the double-ring infiltrometers were placed. The other soils were tested without excavating the surface.

Description of Double-Ring Infiltrometer

A single-ring 30 cm diameter cylinder was gently driven approximately 5 cm into the soil with as little soil disturbance as possible, just far enough to prevent lateral leakage when water is ponded in the cylinder. The surfaces were left in their natural condition and only rocks, woody stems, or other items that may get caught under the cylinder edge when the device was inserted were removed. The plot was flooded using local water, one day in advance in sandy or "soft" soil, or two days in advance in clay or "hard" soils. To avoid rocking the cylinder or pushing first to one side and then to the other, a special driver (slide hammer) consisting of a piece of metal was useful. The slide hammer is a cross brace and a rod with a sliding weight mounted in the center of the cross brace and raising and dropping the weight drives the infiltrometer into the soil. A constant 2 cm water head was automatically maintained in the infiltrometer with a Mariotte-syphon arrangement (Fig. 3).

This device has a stoppered bottle as a water reservoir with a valve at the bottom of the bottle for siphoning water into the infiltrometer, and one tube is inserted through the stopper to allow air to enter the bottle. Adjusting the bubble tube maintained a constant water level in the infiltrometer (constant water head). The principle of the Mariotte syphon is discussed in detail in Bouwer (1986). The soil surfaces were covered with paper towels to minimize surface disturbance when solutions were applied. The single-ring infiltrometer measurements were taken after the steady state infiltration rates were reached. The results were recorded by using the falling-head method, and the height of ponded water was measured to the nearest millimeter.

The double-ring infiltrometer measurements were taken after the steady state infiltration rates were reached in the single-ring infiltrometer measurements. The single-ring cylinder was left in place as an external cylinder, and then a smaller 10 cm diameter cylinder was lightly pushed or gently driven by hand approximately 5 cm into the nearly saturated soil with as little disturbance of the soil as possible. The 2 cm of water head was maintained in the external ring during the recording of steady state infiltration rates in the internal ring using the falling-head method. The height of ponded water in the internal ring was measured to the nearest millimeter, and changes were measured over predetermined time periods.

The field measurements in the Gila, Pima, Vinton, Grabe, Anthony, and Brazito soils used two qualities of water, local water and gypsum water (0.005 M $CaSO_4 \cdot 2H_2O$ - 0.86 g L^{-1}) solution and three replicates were tested (Fig. 1). The field measurements in the Casa Grande, Superstition, and Gadsen soils used three qualities of water, and two replicates: local water, gypsum water (0.86 g of $CaSO_4 \cdot 2H_2O$ / L of deionized water), and gypsum in local water (0.86 g of $CaSO_4 \cdot 2H_2O$ / L of local water) (Fig. 2).

Soil Scientists Field Estimations of Soil Properties

Soil characteristics related to the grittiness, stickiness, plasticity, etc. are the criteria used for estimating particle-size distribution in the field. No single set of characteristics detectable by handling soil material can be used to judge the particle-size distribution of all soils. Specific field criteria for estimating soil texture might be different for soils in different areas. Sand particles can be seen individually with the naked eye and have a gritty feel to the fingers, and most sandy soils are loose. Silt particles cannot be seen individually without magnification; they have a smooth feel to the fingers when dry or wet. In some places clay soils are very sticky such as in soils dominated by montomorillonitic clays, whereas soils that contain large amounts of micaceous or kaolinitic clay are less sticky. Field criteria used to determine the particle size classification of soils are explained in Thien (1979), Soil Survey Staff (1993), Brady and Weil (1999), and others.

Post et al. (1999) evaluated the skill of soil scientists to determine soil texture, stickiness, and plasticity. Plasticity is the degree to which puddled <2 mm soil material is permanently deformed without rupturing by force applied continuously in any direction. The determination of plasticity grouped into four classes as reported in Soil Survey Staff, 1993, and by using a more quantitative procedure as explained in Post et al. (1999).

Stickiness refers to the capacity of puddled <2 mm soil to adhere to other objects and the procedure as described in Soil Survey Staff (1993) and Post et al. (1999) were used. The determination of stickiness will be made as reported in Soil Survey Staff, 1993. Tables 2 and

3 describe these tests, and all evaluation are completed on the <2 mm fine earth soil fractions. A numerical 0-4 rating was computed as described in Table 2 and 3, and in Post et al. (1999).

The procedure for determining the effervescence of soils is described in the Soil Survey Manual (Soil Survey Staff, 1993), and as summarized in Table 4.

Measurements of the none-dispersed particles-size aggregate stability were measured using a wet-sieving method on the less than 2 mm soil fraction. Measurements were made manually by hand, by gently raising and lowering sieves with soil into and out of water. The soil sample weight used for sieve sizes recommended by Burroughs et al. (1992), which were 2.3 gm for the 0.3 mm sieve and 1.4 gm for the 0.075 mm sieve. Ten grams of soil were placed on the USDA 0.25 mm sieve and the procedure as described in the soil quality test kit was followed (Soil Quality Institute, Natural Resources Conservation Service). The soil material remaining on the sieves were oven dried and weighed to determine the percentage retained on each sieve size. The soil material retained on each sieve is reported, and also what is reported as percentage aggregate stability, which is calculated by subtracting the sand weight from the soil material retained on each sieve.

Soil bulk density was measured using the core method as described in Blake and Hartge (1986). Core samplers with cylindrical sleeves and removable sample cylinders that fit inside sleeve samples a relatively undisturbed core, which was oven-dried to determine the mass of dry solids of the bulk volume of soil. Pore volume was calculated using the following equation:

$$\text{Pore Volume} = 100 - \left(\frac{\text{Bulk Density}}{\text{Particle Density}} X100 \right)$$

and the particle density was assumed to be 2.65 g/cm^3

A bulk density "rating" was used in addition to the measured bulk density. The Soil Survey Manual (Soil Survey Staff, 1993) have three generalized figures that show the relationships between soil texture and the measured bulk density. The bulk density ratings are identified as being low, medium, and high. I assigned a code of 0–1 to low, 1–2 to medium, and 2–3 to high bulk densities, using these three figures. This involved the interpolation of the iso-bulk density lines noted on the figures. The rationale for using this rating was to identify relative compactness or density, rather than using absolute bulk density measurements. Using this relative scale might make it easier for field soil scientists to quantify soil bulk density.

Physical and Chemical Laboratory Analyses

Soil samples were collected from the soil profiles after the measurements of steady state infiltration rates were accomplished. The samples were air-dried, crushed, and passed through a 2 mm sieve, and the following analyses were completed on these soils. Analyses were completed by the National Soil Survey Laboratory in Lincoln, NE, and others were competed in the soils laboratory at the University of Arizona. Soil texture was determined by the pipette method as described by Soil Survey Staff (1996). A saturation extract was prepared for chemical analyses, such as EC_e, PH_e, and Sodium Absorption Ration (SAR_e) (mol L^{-1})^2 of the saturation extract (Soil Survey Staff, 1996). Water and soil salinity were determined by using a glass electrode to measure the electrical conductivity (EC) of the water extracts. The concentration of cations Na, Ca, and Mg in the saturation extract and applied water were measured via atomic absorption for calculation of SAR.

Measurements of the none-dispersed particle-size aggregate stability were measured using a mechanical wet-sieving method. The motor of the sieving machine moves at a frequency of 35 cycles/min, gently raising and lowering the sieves into a water bath. The soil sample weight used for each sieve size was within the range recommended by Burroughs et al. (1992), namely 3 g for 0.5 mm sieve, 2.3 g for the 0.3 mm sieve, and 1.4 g for the 0.075 mm sieve. The soil-retained material on the sieves is defined as the none-dispersed particle-size fractions. The material remaining on each sieve were oven dried, and weighed and the percentage of soil particles retained on each sieve size were computed. The mean percentage of aggregate stability was calculated by subtracting the sand weight with size of 2- to selected-mm sieve from soil-retained material (Soil Survey Staff, 1996). Alsharari (1994) describes this procedure.

Soil color was determined using the Chroma Meter colorimeter as described by Post et al. (1993). The mass water content at 2 and 15 bars of tension were measured on <2 mm soil fraction in the National Soil Survey Laboratory. The volumetric water content was measured by two different methods to find the water retention (desorption) curve for undisturbed soil samples. The first method used was a tempe cell with hanging water column (Fig. 4) for low tensions up to about 250 cm water, which is about 1/4 bar. The tempe cell was inverted over the undisturbed soil ring with the soil surface against the porous ceramic plate. The soil samples were saturated from below by keeping a positive head on the tempe

Cell. The second method used was a pressure chamber fitted with a porous ceramic plate. It was used for pressures between 1/3-bar and 15-bar (Klute, 1986). Desorption curve of soils were generated using van Genuchten fitting program from Wraith and Or (1998).

Statistical And Model Evaluation Methods

Evaluation of relationships included using Pearson correlations to measure the linear relationship association with selected soil properties and saturated hydraulic conductivity. The Pearson correlation coefficient, r, measures the strength of a linear relationship between two quantitative variables. The formula is

$$r = \sum_{i=1}^{N} \frac{(x_i - x)(y_i - y)}{(N-1) s_x s_y}$$

where N is the sample size and s_x *and* s_y are the standard deviations of the two variables (SPSS Base 10, 1999).

The curve estimation procedure was used to produce the best curve regression statistics, and plots for 11 different curve estimation regression models were evaluated. A separate model was produced for each dependent variable. When there is only one independent variable, R is the simple correlation between the dependent and independent variable. R^2 is values range from 0 to 1. If there is no linear relation between the dependent and independent variable, R^2 is 0 or very small. If all the observations fall on the regression line, R^2 is 1. This measure of the goodness of fit of linear model is also called the coefficient

of determination. It is the proportion of variation in the dependent variable explained by the regression model.

R^2 is also defined as:

$$R^2 = \frac{SSR}{SST}$$

where SSR is the regression sum of squares measuring the variability in the response variable attributed to the model, SST is the sum of squares corrected for the mean for the response variable (which measures the total variability in the response variable). For multiple regression models, R is the correlation between the observed and predicted values of the dependent variable (for this study, the correlation between K_{sat} and the values of K_{sat} predicted by the model). The sample estimate of R^2 tends to be an overestimate of the population parameter. The adjusted R^2 is designed to compensate for the optimistic bias of R^2. It is function of R^2 adjusted (R^2_{adj}) by the number of variables in the model and sample size:

$$R^2_{adj} = R^2 - \frac{p(1 - R^2)}{N - P - 1}$$

where P is the number of independent variables in the equation.

or

$$R^2_{adj} = 1 - \frac{\text{reidual sum of squares} / \ (N - P - 1)}{\text{total sum of squares} \ / \ (N - 1)}$$

The value of R^2_{adj} is always smaller than corresponding R^2 (SPSS Base 10, 1999).

Another statistic used to aid selection of a final model is called Mallow's C_p defined as:

$$C_p = (\frac{SSE_p}{MSE}) + 2p - n + 1$$

where MSE is the error mean square for full model, and SSE_p is the error sum of squares for a model with p parameters (not including the intercept) by Freund and Littell, (1991). This model chooses the maximum R^2_{adj}, which gave the smallest $C_p \approx$ the number of beta (β_s) in the model.

In this study K_{sat} was the dependent variable, and the soil characteristics were the independent variables. The Pearson correlations and the best curve estimation regression were investigated to show the relationship between K_{sat} values followed by stepwise multiple regression analysis. The soil scientists field morphology data including plasticity, stickiness, and other, morphological descriptions test were made by eight soil scientists individually, and the average of these different estimations were used as an independent variable.

Stepwise multiple regression analysis was produced to predict soil hydraulic conductivity from independent soil variables. The stepwise method begins by entering into the model the variable that has the strongest positive or negative correlation with the dependent variable, and at each subsequent step adds the variable with the strongest partial correlation, and at each step variables are tested for removal. The output analysis of the regressions procedure was generated using SPSS Base, 1999 software, Version [10].

Therefore, four steps will be utilized as follows:

1- An all-possible-regressions procedure was used to generate variable reductions. The purpose of this approach is to identify a small group of regression models that are "good" according to specified criterion R^2 and R^2_{adj} and/or C_p, so that a detailed examination can be made of these models, leading to the selection of the final regression model to be used.

2- Diagnostic Eigenvalues are obtained by factoring the scaled (so that diagonal elements are 1's), uncentered cross-products matrix of the independent variables. Eigenvalues provide an indication of how many distinct dimensions there are among the independent variables of selected models note. When Eigenvalues are close to 0, the variables are highly intercorrelated and the matrix is said to be *ill*-conditioned (small changes in the data values may lead to large changes in the estimates of coefficients).

3- Casewise diagnostics using residuals statistics are obtained by calculating a predicted value for each case K_{sat}. For each case (K_{sat}), the residual is the difference between the observed value of the dependent variable (K_{sat}) and the value predicted by model.

4- The standard error of mean and a student's t-test were also used to compare the field measurements versus model simulations. A comparison was made between the mean of measurements and the mean of predictions using the student's t-test for the null hypothesis of no significant differences (Steel and Torrie, 1980).

RESULTS

Table 5 presents the steady state infiltration rates (cm/hr) for the ten irrigated soils measured in this study. Table 6 presents the laboratory characterization for the ten irrigated soils evaluated in this study. Table 7 summaries the mean results of eight individual soil scientists' estimations made for % clay, % sand, plasticity, stickiness and effervescence. Table 8 presents data for bulk density and Table 9 the chemical analyses of the saturation pastes collected after the steady state infiltration rates were measured, Table 10 the chemical properties of the waters, and Table 11 lists the none-dispersed particle-size data and aggregate stability for the ten soils. Table 12 presents the soil moisture release curves measured on the undisturbed soil cores for the ten soils.

Two groups of quantified soil properties were evaluated in this study, namely soil properties estimated by soil scientists (Table 13) and soil properties measured by laboratory analyses (Table 17). Both data sets were used as independent variables in best curve estimation and individual stepwise multiple regressions.

Simple linear regressions were computed for clay and sand percentages laboratory measurements verses clay and sand percentage estimations of field soil scientists (Figures 5 and 6). Both regressions of % clay and % sand produced high R^2 (0.98 and 0.95, respectively) and slope values (a coefficient) (1.17 and 1.10, respectively) which indicated that soil scientists' estimations were comparable to laboratory analyses estimations.

Soil Properties Estimated by Field Soil Scientists as Predictor Variables for K_{sat}

Pearson correlations (r) and best curve were computed using all ten soils series as a cluster (Table 13) and nine soils (Brazito soil excluded) as another cluster (Table 14). I chose to exclude the very sandy Brazito soil because of its high intake rate, which significantly affected my statistical analysis and because it was out of the normal range for most K_{sat} value soils. These soil properties were further examined as predictor variables for K_{sat} in stepwise multiple-regression. Stepwise multiple-regression criteria were set at probability of F to enter ≤ 0.5 and probability of F to remove ≥ 0.1.

The first run was undertaken to compute a stepwise multiple-regression using all soil properties estimated in the field by soil scientists as the independent variables (Table 15). A subset of five predicator variables were selected: effervescence, none-dispersed particle-size on 0.3 mm sieves, none-dispersed particle-size on 0.075 mm sieves, aggregate stability on 0.3 mm sieves, bulk density, and constant to predict the dependent variables K_{sat} (Table 15). The R^2, R^2_{adj}, and C_p were 0.992, 0.991, and 18.705, respectively. The comparison of predicted and measured K_{sat} to test validation (Table 16) gave a negative predicted value for the Gadsen soil, which is evidence of this model's limitation, because K_{sat} cannot be negative. Moreover, stepwise multiple-regression selected effervescence as the first variable entered because effervescence gave the strongest negative simple correlation with the dependent variables, and it eliminated independent variables at each subsequent step. The Brazito sand of course had the highest K_{sat}, but it was also the only soil that was non-calcareous, so statistically this is recognized as being very important. The stepwise multiple-regression procedure is not guaranteed to provide the best subset in an absolute sense. The casewise diagnostics obtained by the residual is the difference between the observed value of the dependent variables (K_{sat}) and the value predicted by model. Therefore, the effervescence variable was deleted from the independent variable selection in run 2.

Run 2 was done to compute stepwise multiple-regression using all soil properties estimated in field by soil scientists excluding effervescence as independent variables. Subset of eight predictor variables were selected: aggregate stability on 0.25 mm sieves, aggregate stability on 0.075 mm sieves, none-dispersed particle-size on 0.075 mm sieves, aggregate stability on 0.3 mm sieves, none-dispersed particle-size on 0.3 sieves, none-dispersed particle-size on 0.25 mm sieves, bulk density, % sand estimations and constant to predict the dependent variable K_{sat}. This is called *Model A* (Table 15). The R^2, R^2_{adj}, and C_p were 0.994, 0.993, and 8.071, respectively. The comparison of predicted and measured K_{sat} to test validation (Table 16) gave fair predicted value of all soils, which suggest this is an adequate model. Figure 8 plots the relationship between the measured and predicted K_{sat} for *Model A*.

Run 3 was done to compute stepwise multiple-regression with five soil properties commonly estimated by field soil scientists, namely % clay, % sand, stickiness, plasticity and bulk density. A subset of two predictor variables were selected, plasticity, bulk density, and the constant (Table 15). The R^2, R^2_{adj} and C_p were 0.388, 0.366, and 3.997, respectively. The comparison of predicted and measured K_{sat} to test validation (Table 16) gave negative predicted values for Pima, Casa Grande SCL, and Gadsen soils and overestimated for the Gila, Vinton, Grabe, Anthony, Casa Grande SL and Superstition soils. The Brazito soil was greatly underestimated, which is further evidence of model limitations.

Since stepwise multiple-regression selection that enters variables depends on the strongest positive (or negative) simple correlation with the dependent variables K_{sat}, my personal judgment was to select independent variables that produce an adequate model from several runs. Run 4 produced *Model B* and a subset of eight predictor variables were selected: plasticity, aggregate stability on 0.25 mm sieves, % clay estimations, bulk density, aggregate on 0.3 mm sieves, none-dispersed particle-size on 0.075 mm sieves, none-dispersed particle-size on 0.25 mm sieves, % sand estimations, and constant (Table 15). The R^2 and R^2_{adj}, and C_p were 0.997, 0.994, and 9.000, respectively. The comparison of predicted and measured K_{sat} to test validation (Table 16) gave a fair predicted value for all soils, which suggest this is an adequate model. Figure 9 plots the relationship between the measured and predicted K_{sat} for *Model B*.

Another way to evaluate the data is to exclude Brazito soil, because of its very sandy character and very high K_{sat}. My personal judgment is to select independent variables that produce appropriate model from two or more runs. Run 5 produced *Model C* where a subset of six predictor variables were selected: none-dispersed particle-size on 0.075 mm sieves, % sand estimations, % clay estimations, rating bulk density, bulk density, stickiness, and constant (Table 15). The R^2, R^2_{adj} and C_p were 0.884, 0.870, and 7.000, respectively. The comparison of predicted and measured K_{sat} to test validation (Table 16) gave fair predicted values for all soils. Figure 10 plots the relationship for the measured and predicted K_{sat} for this model. *Model C* restricts soil textures from sandy loam to silty clay loam, and this model will not work for very sandy soil.

Laboratory Measured Soil Properties as Predictor Variables for K_{sat}

Pearson correlations (r) and best curve estimations were computed using all ten soils series as a cluster (Table 17) and for nine soils (Brazito soil excluded) as another cluster (Table 18) to study the relationships between soil properties measured using laboratory analyses and K_{sat}. These soil properties were examined as predictor variables K_{sat} in a stepwise multiple-regression.

The first run used all laboratory measured soil properties as independent variables. Subset of nine predictor variables were selected: % find sand, % total sand, % volumetric water content at 100 kPa, % clay, % very coarse sand, aggregate stability on 0.075 mm sieves, SAR of soil, % volumetric water content at 1 kPa, SAR of water and the constant to predict the dependent variable K_{sat}, which is called *Model D* (Table 19). The R^2, R^2_{adj}, and C_p were 0.995, 0.994, and 10.599, respectively. The comparison of predicted and measured K_{sat} to test validation (Table 20) gave fair predicted values of all soils, which is evidence of an adequate model (Fig. 11).

Run 2 was done to compute stepwise multiple-regression to examine selected morphological and physical soil properties using laboratory analyses without chemical soil properties. The selected soil properties were % clay, % silt, % total sand, % very fine sand, % fine sand, % medium sand, % coarse sand, % very coarse sand, bulk density, rating of bulk density, none-dispersed particle-size on 0.3 mm sieves, none-dispersed particle-size on 0.075 mm sieves, aggregate stability on 0.5 mm sieves, aggregate stability on 0.3 mm sieves, aggregate stability on 0.075 mm sieves, % volumetric water content at 1 kPa, % volumetric water content at 33 kPa, % volumetric water content at 100 kPa, and % volumetric water content at 1500 kPa. The subset selection of stepwise multiple-regression was six predictor variables: % fine sand, % total sand, volumetric water content at 100 kPa, % clay, % very coarse sand, aggregate stability on 0.075 mm sieves, and the constant which is called *Model E* (Table 19). The R^2, R^2_{adj}, and C_p were 0.997, 0.994, and 4.076, respectively. The comparison of predicted and measured K_{sat} to test validation (Table 20) gave an adequate predicted value of soils (Fig. 12).

Another interesting way is provide model fit soils exclude Brazito soil (sandy texture). (My personal judgment is to select independent variables that produce appropriate model from several runs.) Those several runs (Run 3) produced *Model F*. Subset set of six predictor variables were selected: % very fine sand, volumetric water content at 1 kPa, % clay, rating of bulk density, % silt, % very coarse sand, % aggregate stability on 0.5 mm sieves, and constant (Table 19). The R^2, R^2_{adj} and C_p were 0.882, 0.864, and 8.272, respectively. The comparison of predicted and measured K_{sat} to test validation (Table 20) gave a fair predicted value of all soils, which is evident of an adequate model (Fig. 13). *Model F* restricted to the soil textures ranged from sandy loam to silty clay loam, because only nine soils out of ten soils were used as regressor to determine the dependent variable. *Model F* will not work for high sand contents soils.

COLLINEARITY DIAGNOSTICS

Eigenvalues are obtained by factoring the scaled (so that diagonal elements are 1's), uncentered cross-products matrix of the independent variables. Eigenvalues provide an indication of how many distinct dimensions there are among the independent variables (Tables 21 and 22) of selected models. When eigenvalues are close to 0, the variables are highly intercorrelated and the matrix is said to be *ill*-conditioned (small changes in the data values may lead to large changes in the estimates of coefficients). Therefore, I examined collinearity diagnostics suggestion by deleting one or more variables, which have had eigenvalues close to 0 from the selection as independent variables and reruns stepwise multiple-regression. These reruns provided insufficient subset models that produced poor estimations for K_{sat} values when the casewise diagnostics was computed to test validation.

MODELS VALIDATION

The *Models A, B, D,* and *E* predicted values were tested against measured data of field saturated hydraulic conductivity obtained from ten soils. Measured data of field saturated hydraulic conductivity obtained from nine soils (Brazito soil excluded) were used in comparison to *Model C* and *F*: A student's t-test was used to compare predicted K_{sat} estimations to measured values of soils hydraulic conductivity (Table 23). The test (t = 0., P > 0.) showed that there were no statistically significant differences between the mean of predicted and mean of measured values of saturated soil hydraulic conductivity at the 0.01 probability level. Graphic depiction (Fig. 8, 9, 10, 11, 12, and 13) showed that the data points are uniformly scattered around the 1:1 line. This statistically reasonable agreement between the measured and modeled results suggests that models A, B, C, D, E, and F performed well; thus the models were satisfactorily validated.

DISCUSSION AND CONCLUSION

Six new models are proposed to predict hydraulic conductivity of Arizona irrigated soils, and they are noted below. Models A,B, and C use soil morphology data provided by field soil scientists, and Models D, E, and F use soil properties determined or measured by lab analysis. Model C and model F are restricted to predict hydraulic conductivity of soil textures ranging from sandy loam to silty clay.

Model A = K_{sat} (cm/hr)	+ 2.366 (aggregate stability on 0.25 mm sieves) – 0.535 (aggregate stability on 0.075 mm sieves) + 0.377 (none-dispersed particle-size on 0.075 mm sieves) – 2.148 (aggregate stability on 0.3 mm sieves) + 1.697 (none-dispersed particle-size on 0.3 sieves) – 1.214 (none-dispersed particle-size on 0.25 mm sieves) + 31.933 (bulk density) + 0.173 (% sand estimations) – 89.749
	R^2 = 0.994 R^2_{adj} = 0.993 C_p = 8.071
Model B = K_{sat} (cm/hr)	+ 11.823 (Plasticity) + 3.747 (aggregate stability on 0.25 mm sieves) – 2.520 (% clay estimations) + 171.083 (bulk density) + 3.747 (aggregate on 0.3 mm sieves) + 1.046 (none-dispersed particle-size on 0.075 mm sieves) – 1.595 (none-dispersed particle-size on 0.25 mm sieves) + 0.324 (% sand estimations) – 353.158
	R^2 = 0.997 R^2_{adj} = 0.994 C_p = 9.000
Model C = K_{sat} (cm/hr)	- 0.107 (none-dispersed particle-size on 0.075 mm sieves) + 0.126 (% sand estimations) + 0.003385 (% clay estimations) + 4.718 (rating bulk density) – 9.572 (bulk density) + 0.923 (stickiness) + 6.841
	R^2 = 0.884 R^2_{adj} = 0.870 C_p = 7.000
Model D = K_{sat} (cm/hr)	+ 1.683 (% find sand) – 0.800 (% total sand) – 202.466 (% volumetric water content at 100 kPa) + 0.593 (% clay) +1.402 (% very coarse sand) + 0.0860 (aggregate stability on 0.75 mm sieves) – 0.819 (SAR of soil) + 109.136 (% volumetric water content at 1 kPa) + 0.231 (SAR of water) + 8.002
	R^2 = 0.995 R^2_{adj} = 0.994 C_p = 10.599
Model E = K_{sat} (cm/hr)	+ 1.866 (% fine sand) – 0.800 (% total sand) – 125.789 (volumetric water content at 100 kPa) + 0.728 (% clay) + 1.610 (% very coarse sand) + 0.245 (aggregate stability on 0.075 mm sieves) + 3.007
	R^2 = 0.997 R^2_{adj} = 0.994 C_p = 4.074
Model F = K_{sat} (cm/hr)	+ 1.002 (% very fine sand) – 46.550 (volumetric water content at 1 kPa) + 0.600 (% clay) - 0.202 (% silt) + 0.881 (% very coarse sand) + 0.07787 (% aggregate stability on 0.5 mm sieves) + 20.540
	R^2 = 0.882 R^2_{adj} = 0.864 C_p = 8.272

It should be recognized that the suggested models in this study are limited to the observed samples. The six empirical models ensured their best performance for quick and economic estimations of necessary model input parameters, particularly for regional-scale of irrigated soils studied.

Recently, many pedotransfer functions (PTFs) models have been published for estimating soil hydraulic conductivity. Therefore, I decided to evaluate the performance of the most widely and popular used model by comparing the measured K_{sat} values of soils series that I used in my study to the predicted values using Rosetta models. Rosetta pedotransfer functions developed by Schaap and Leij, (1999) were used to determine the soil hydraulic conductivity.

Rosetta offers five PTFs that allow prediction of the hydraulic properties with limited or more extended sets of input data. This hierarchical approach is of a great practical value because it permits optimal use of available input data. The models use the following hierarchical sequence of input data:

Model 1: Soil textural class.

Model 2: Sand, silt and clay percentages.

Model 3: Sand, silt and clay percentages and bulk density.

Model 4: Sand, silt and clay percentages, bulk density and a water retention point at 330 cm (33 kPa).

Model 5: Sand, silt and clay percentages, bulk density and water retention points at 330 and 15000 cm (33 and 1500 kPa).

The first model is based on a lookup table that provides class average hydraulic parameters for each USDA soil textural class. The other four models are based on neural network analyses and provide more accurate predictions when more input variables are used.

All estimated hydraulic parameters are accompanied by uncertainty estimates that permit an assessment of the reliability of Rosetta's predictions. These uncertainty estimates were generated by combining the neural networks with the bootstrap method (Schaap and Leij 1998; Schaap et al., 1999).

Table 24 presents the K_{sat} (cm/hr) for the ten irrigated soils measured in this study and the estimations values of K_{sat} (cm/hr) from Rosetta pedotransfer models. The predicted value from Model 1 and Model 2 compared to measured K_{sat} (Table 24) underestimated Vinton and Brazito soils and overestimated the Superstition soil. The predicted value from Models 3, 4, and 5 was performed in closer agreement with measured K_{sat} values, except the models greatly underestimated Vinton, Pima, and Gadsen soils and overestimated for the Casa Grande SCL and Superstition soils. It is evident that the use of Rosetta models 4 and 5 generally resulted in a poor performance of predicting K_{sat} values for most soils series that was used in my study. Models 1, 2, and 3 performed fairly well in predicting Grabe, Anthony, Gadsen, and Casa Grande SL soils K_{sat} values. Figures 14 and 15 are graphical comparison of Rosetta models estimations and measured K_{sat}.

Table 1. List of soil series, texture, family taxonomic classification, and sample location for ten irrigated Arizona soils.

Soil Series	Texture	Family Taxonomic Classification	Sample Location
Gila	VFSL	Coarse-loamy, mixed, superactive, calcareous, thermic Typic Torrifluvents	East Agricultural Center, Tucson
Pima	SiCl	Fine-silty, mixed (calcareous), thermic Typic Torrifluvents	East Agricultural Center, Tucson
Vinton	FSL	Sandy, mixed, thermic Typic Torrifluvents	USDA Plant Material Center, Tucson
Grabe	L	Coarse-loamy, mixed, calcareous, thermic Typic Torrifluvents	USDA Plant Material Center, Tucson
Anthony	VFSL	Coarse-loamy, mixed, superactive, calcareous, thermic Typic Torrifluvents	USDA Plant Material Center, Tucson
Brazito	S	Mixed, thermic Typic Torripsamments	West Agricultural Center, Tucson
Casa Grande SL	SL	Fine-loamy, mixed, superactive, hyperthermic Typic Natrargids	Agricultural Center, Maricopa
Casa Grande SCL	SCL	Fine-loamy, mixed, superactive, hyperthermic Typic Natrargids	Agricultural Center, Maricopa
Superstition	LS	Sandy, mixed, hyperthermic Typic Haplocalcids	Agricultural Center, Yuma
Gadsen	SiC	Fine, smectic, calcareous, hyperthermic vertic Torrifluvent	Agricultural Center, Yuma

Table 2. Description of plasticity classes

Code	Classes	Test Description
0-1	Non-plastic	A roll 4 cm long and 6 mm thick that supports its own weight held on end cannot be formed.
1-2	Slightly plastic	A roll 4 cm long and 6 mm thick can be formed and, if held on end, will support its own weight. A roll 4 mm thick will not support its own weight.
2-3	Moderately plastic	A roll 4 cm long and 4 mm thick can be formed and will support its own weight, but a roll 2 mm thick will not support its own weight.
3-4	Very plastic	A roll 4 cm long and 2 mm thick can be formed and will support its own weight.

Source: Soil Survey Staff, Soil Survey Manual, USDA Handbook No. 18, 1993.

Table 3. Description of stickness classes

Code	Classes	Test Description
0-1	Non-sticky	After release of pressure, practically no soil material adheres to thumb or forefinger.
1-2	Slightly sticky	After release of pressure, soil material adheres perceptibly to both digits. As the digits are separated, the material tends to come off one or the other rather cleanly. The material dose not stretch appreciably on separation of the digits.
2-3	Moderately sticky	After release of pressure, soil material adheres to both digits and tends to stretch slightly rather than pull completely free from either digit.
3-4	Very sticky	After release of pressure, soil material adheres so strongly to both digits that it stretches decidedly when the digits are separated. Soil material remains on both digits.

Source: Soil Survey Staff, Soil Survey Manual, USDA Handbook No. 18, 1993.

Table 4. Description of effervescence classes

Code	Classes	Test Description
0	None effervescent	No bubbles seen
.1-1	Very slightly effervescent	Few bubbles seen
1-2	Slightly effervescent	Bubbles readily seen
2-3	Strongly effervescent	Bubbles form low foam
3-4	Violently effervescent	Thick foam forms quickly

Source: Soil Survey Staff, Soil Survey Manual, USDA Handbook No. 18, 1993.

Table 5. Steady state infiltration rates (cm/hr) data for study sites.

Soil Series	Water Type	Infiltrations Rate (cm/hr)	$\bar{x}$
Gila	1	1.10, 1.21, 1.02	1.11
	2		
	3	0.70, 0.48, 0.22	0.47
Pima	1	0.19, 0.41, 0.20	0.27
	2		
	3	0.39, 0.63, 0.67	0.56
Vinton	1	7.96, 5.17, 7.32	6.82
	2		
	3	4.43, 4.70, 5.05	4.73
Grabe	1	0.11, 0.69, 0.79	0.53
	2		
	3	0.42, 0.41, 0.43	0.42
Anthony	1	1.13, 0.75, 1.32	1.07
	2		
	3	2.63, 1.32, 0.81	1.59
Brazito	1	46.53, 42.32, 41.26	43.37
	2		
	3	49.14, 47.97, 45.19	47.43
Casa Grande SL	1	1.32, 1.04	1.18
	2	2.56, 2.32	2.44
	3	2.54, 2.32	2.43
Casa Grande SCL	1	0.15, 0.37	0.26
	2	1.09, 0.69	0.89
	3	0.12, 0.22	0.17
Superstition	1	1.98, 1.58	1.78
	2	2.18, 1.11	1.65
	3	1.19, 1.58	1.39
Gadsen	1	0.24, 0.24	0.24
	2	0.27, 0.63	0.45
	3	0.32, 0.37	0.35

1) Local water. 2) Gypsum in local water. 3) Gypsum water.

Table 6. Laboratory characterization data for soils.

Soil Series	Horizon	Text. Class.	Depth (cm)	Clay	Silt		% Sand						Soil CO_3
				Total	Total	Fine	Total	VF	F	M	C	VC	
Gila	Ap1	VFSL	0-16	9.7	34.3	13.1	56.0	22.3	22.4	5.9	2.9	2.5	4
	Ap2	VFSL	16-42	9.1	35.8	14.2	55.1	24.5	20.8	5.0	3.2	1.6	5
	C	L	42-100	8.9	48.7	20.4	42.4	22.5	16.3	3.0	0.5	0.1	5
Pima	Ap1	SiCl	0-30	33.2	49.8	30.5	17.0	9.0	3.8	1.7	1.6	0.9	10
	Ap2	SiCl	30-60	32.5	48.9	28.1	18.6	8.2	4.4	2.1	1.9	2.0	9
	C	SiCl	60-90	32.1	49.6	28.8	18.3	9.3	4.1	2.0	1.8	1.1	9
Vinton	Ap1	FSL	0-17	7.7	20.3	7.8	72.0	21.6	33.5	11.7	3.8	1.4	2
	Ap2	FSL	17-71	6.7	24.3	8.7	69.0	27.8	32.5	6.9	1.4	0.4	2
	C	SiL	71-100	10.7	60.4	23.1	28.9	20.0	6.9	1.5	0.4	0.1	3
Grabe	Ap1	L	0-18	24.2	38.4	19.8	37.4	18.0	14.2	3.9	0.9	0.4	4
	Ap2	L	18-45	18.4	36.4	16.0	45.2	18.7	18.7	5.8	1.4	0.6	6
	C1	SiL	45-85	17.5	52.0	23.7	30.5	18.4	9.3	2.3	0.4	0.1	8
	C1	SiL	85-100	13.9	68.1	32.5	18.0	12.7	4.0	0.9	0.2	0.2	5
Anthony	Ap1	VFSL	0-24	13.0	30.5	14.1	56.5	19.9	24.2	8.8	2.8	0.8	3
	Ap2	FSL	24-50	13.0	21.9	11.5	65.1	17.7	29.9	13.1	3.2	1.2	3
	C	VFSL	50-80	17.2	29.5	12.8	53.3	25.5	23.0	3.7	1.0	0.1	4

Table 6. Continued

Soil Series	Horizon	Depth (cm)	2 Bar	15 Bar	1500 kPa: Clay ratio	Aggregate stability on 0.5 mm	Color	
							Dry	Wet
Gila	Ap1	0-16	9.6	6.5	.67	6	9.6 YR 6.0 / 3.2	9.2 YR 4.1 / 3.2
	Ap2	16-42	9.3	6.4	.70	4	9.8 YR 6.0 / 3.2	9.0 YR 3.8 / 2.9
	C	42-100	10.6	6.7	.75	37	9.3 YR 6.0 / 3.2	8.9 YR 4.3 / 3.6
Pima	Ap1	0-30	19.1	14.5	.44	34	9.6 YR 5.3 / 2.6	8.1 YR 3.0 / 2.1
	Ap2	30-60	20.6	14.7	.45	7	9.2 YR 5.7 / 3.0	8.4 YR 3.8 / 2.6
	C	60-90	18.8	14.1	.44	19	9.4 YR 5.2 / 2.7	8.5 YR 3.3 / 2.3
Vinton	Ap1	0-17	7.2	5.5	.71	6	9.3 YR 5.0 / 2.9	8.8 YR 3.6 / 2.7
	Ap2	17-71	7.0	5.3	.79	2	9.3 YR 5.5 / 3.0	8.9 YR 4.0 / 2.8
	C	71-100	10.3	7.7	.72	0	9.3 YR 6.0 / 3.0	8.9 YR 4.1 / 2.9
Grabe	Ap1	0-18	16.3	12.0	.50	2	9.2 YR 4.3 / 2.4	8.2 YR 2.8 / 2.1
	Ap2	18-45	14.3	10.6	.58	5	8.9 YR 5.2 / 2.8	8.2 YR 3.4 / 2.6
	C1	45-85	15.1	10.6	.61	5	8.9 YR 5.3 / 3.0	8.6 YR 3.9 / 2.9
	C1	85-100	12.9	9.4	.68	2	9.3 YR 5.1 / 3.2	8.8 YR 4.0 / 3.0
Anthony	Ap1	0-24	10.1	7.3	.56	2	9.1 YR 5.2 / 3.0	8.5 YR 3.6 / 2.8
	Ap2	24-50	8.9	6.6	.63	18	8.9 YR 5.3 / 3.2	8.6 YR 4.0 / 2.9
	C	50-80	13.2	9.7	.56	4	8.9 YR 4.9 / 2.8	8.1 YR 3.1 / 2.3

Table 6. Continued

Soil Series	Horizon	Text. Class.	Depth (cm)	Clay Total	Silt		% Sand						Soil CO_3
					Total	Fine	Total	VF	F	M	C	VC	
Brazito	C1	S	0-28	0.5	0.5	0	99	15.7	65.65	17.33	0.31	0.01	0
	C2	S	28-61	0.5	0.5	0	99	15.7	65.65	17.33	0.31	0.01	0
	C3	S	61-103	0.5	0.5	0	99	15.7	65.65	17.33	0.31	0.01	0
Casa Grande SL	Ap1	SL	0-18	14.5	18.2	6.6	67.3	11.1	20.0	18.3	11.3	6.6	2
	Ap2	SL	18-53	14.5	18.5	6.9	67.0	11.7	19.7	18.4	11.7	5.5	2
	Btk	SCL	53-100	24.1	26.6	16.7	49.3	10.8	17.1	12.4	6.1	2.9	17
Casa Grande SCL	Ap1	SCL	0-25	20.8	17.3	6.9	61.9	11.9	19.4	16.6	10.7	3.3	1
	Ap2	SL	25-58	13.8	18.9	5.8	67.3	13.8	21.3	17.7	10.8	3.7	2
	Btk1	SL	58-99	10.6	17.8	3.9	71.6	12.9	20.4	19.8	14.6	3.9	1
	Btk2	SL	99-125	13.3	20.0	9.8	66.7	10.1	17.6	20.3	13.8	4.9	8
Superstition	Ap1	LS	0-25	6.8	8.1	1.9	85.1	16.0	33.8	26	8.4	0.9	4
	Ap2	LS	25-35	7.0	7.9	3.4	85.1	14.3	32.7	27.7	9.3	1.1	6
	C1	LS	35-75	7.3	9.6	4.2	83.1	10.3	34.9	31.2	5.6	1.1	6
	C2	S	75-100	3.7	3.3	1.2	93.0	7.0	37.2	39.6	8.1	1.1	4
Gadsen	Ap	SiC	0-55	46.5	42.7	35.1	10.8	6.9	3.6	0.3	Tr	Tr	11
	2C	LVFS	55-115	2.2	13.6	1.9	84.2	52.6	30.7	0.9	Tr	Tr	7

Table 6. Continued

Soil Series	Horizon	Depth (cm)	2 Bar	15 Bar	1500 kPa: Clay ratio	Aggregate Stability on 0.5 mm	Color	
							Dry	Wet
Brazito	C1	0-28		4.5	0.11	0.00	9.1 YR 6.2/2.1	8.9YR 4.3/2.2
	C2	28-61		4.5	0.11	0.00	9.1 YR 6.2/2.1	8.9YR 4.3/2.2
	C3	61-103		4.5	0.11	0.00	9.1 YR 6.2/2.1	8.9YR 4.3/2.2
Casa Grande SL	Ap1	0-18	8.5	7.0	0.48	0	7.4 YR 5.2 / 4.3	6.9 YR 4.0 / 4.3
	Ap2	18-53	8.2	6.7	0.46	57	7.0 YR 5.2 / 4.7	6.7 YR 4.1 / 4.7
	Btk	53-100	12.8	10.1	0.42	65	6.8 YR 6.0 / 4.5	6.5 YR 4.5 / 5.0
Casa Grande SCL	Ap1	0-25	10.6	8.7	0.42	10.6	6.9 YR 5.1 / 4.1	6.7 YR 4.0 / 4.3
	Ap2	25-58	7.5	5.9	0.43	7.5	6.9 YR 5.4 / 4.9	6.7 YR 4.1 / 4.6
	Btk1	58-99	5.5	4.5	0.42	5.5	7.0 YR 5.4 / 4.9	6.6 YR 4.3 / 4.7
	Btk2	99-125	7.4	5.9	0.44	7.4	6.3 YR 6.0 / 4.4	6.8 YR 4.9 / 4.9
Superstition	Ap1	0-25	4.3	3.2	0.47	4.3	8.5 YR 5.4 / 3.6	8.1 YR 4.3 / 3.9
	Ap2	25-35	5.0	3.7	0.53	5.0	8.2 YR 5.6 / 3.6	8.4 YR 4.7 / 3.9
	C1	35-75	4.7	3.7	0.51	4.7	8.1 YR 5.8 / 3.8	8.1 YR 5.1 / 4.4
	C2	75-100	2.5	2.2	0.59	2.5	8.5 YR 5.8 / 3.8	8.5 YR 5.0 / 4.3
Gadsen	Ap	0-55	27.4	20.7	0.45	27.3	8.9 YR 5.3 / 2.8	7.6 YR 4.0 / 2.7
	2C	55-115	2.4	2.0	0.91	2.4	8.2 YR 6.0 / 3.6	8.0 YR 4.9 / 3.6

Table 7. Mean of field estimations of selected soil morphologic properties by eight professional soil scientists.

Soil Series	Horizon	% Clay		% Sand		Plasticity		Stickiness		Effervescence	
		$\bar{x}$	St. Dev.	$\bar{x}$	St. Dev.	$\bar{x}$	St. Dev.	$\bar{x}$	St. Dev.	$\bar{x}$	St. Dev.
Gila	Ap	11.9	5.0	62.7	12.0	1.36	0.85	1.20	0.50	3.25	0.66
Pima	Ap	38.0	15.6	6.5	3.6	3.61	0.40	3.09	0.58	3.75	0.66
Vinton	Ap	7.1	2.1	74.9	8.6	0.64	0.47	0.74	0.43	2.88	1.17
Grabe	Ap	19.9	6.1	28.3	13.1	2.44	0.31	1.89	0.43	3.25	0.83
Anthony	Ap	16.3	4.9	58.0	11.6	1.59	0.89	1.35	0.61	3.25	0.66
Brazito	Ap	1.0	4.1	98.0	4.5	0.05	3.1	0.05	0.32	0.00	0.00
Casa Grande SL	Ap	19.8	8.0	67.1	8.2	2.04	0.47	2.00	0.63	3.25	0.43
Casa Grande SCL	Ap	27.8	7.7	61.4	7.0	3.09	0.63	2.84	0.48	3.25	0.83
Superstition	Ap	4.4	2.2	83.6	7.4	0.60	0.93	0.28	0.20	3.63	0.70
Gadsen	Ap	53.6	19.4	8.7	6.7	3.61	0.46	3.06	0.85	3.75	0.43

Table 8. Bulk density and "Rating" for bulk density.

Soil Series	Horizon	Bulk Density (g/cm^3)	$\bar{x}$	"Rating" For Bulk Density
Gila	Ap	1.54, 1.49, 1.45, 1.42	1.48	1.5
Pima	Ap	1.78, 1.88, 1.71, 1.77	1.79	3.0
Vinton	Ap	1.62, 1.44, 1.50, 1.55	1.53	1.5
Grabe	Ap	1.57, 1.53, 1.45, 1.42	1.49	2.2
Anthony	Ap	1.44, 1.49, 1.54, 1.64	1.53	1.8
Brazito	Ap	1.46, 1.46, 1.43	1.45	0.9
Casa Grande	Ap	1.58, 1.61, 1.63, 1.58	1.60	2
Casa Grande	Ap	1.42, 1.69, 1.59, 1.55	1.56	1.7
Superstition	Ap	1.79, 1.78, 1.73, 1.72	1.76	2.1
Gadsen	Ap	1.51, 1.47, 1.45, 1.43	1.47	2.5

Table 9. Chemical analysis results of saturated soil paste extracts after steady state infiltration rates measurements.

Soil Series	Water Type	EC_e	$\bar{x}$	pH_e	$\bar{x}$	SAR	$\bar{x}$
Gila	1	0.80, 0.81, 1.09	0.90	8.52, 7.04, 7.04	7.53	4.01, 3.60, 3.41	3.7
	2						
	3	0.97, 0.83, 0.94	0.91	7.23, 7.23, 8.38	7.61	3.17, 3.18, 2.93	3.1
Pima	1	0.82, 0.84, 0.90	0.85	7.15, 7.13, 7.33	7.20	7.07, 7.20, 6.55	6.9
	2						
	3	1.09, 0.93, 0.92	0.98	7.33, 7.27, 7.19	7.26	5.99, 6.26, 6.63	6.3
Vinton	1	0.81, 0.83, 0.71	0.78	6.58, 8.50, 7.85	7.64	6.37, 7.01, 7.25	6.9
	2						
	3	0.88, 1.02, 1.04	0.98	7.77, 7.52, 7.02	7.44	6.24, 6.26, 6.72	6.4
Grabe	1	0.83, 0.79, 0.75	0.79	6.90, 7.29, 8.17	7.45	7.62, 7.73, 7.31	7.6
	2						
	3	0.93, 1.05, 0.86	0.95	7.31, 7.02, 6.75	7.03	7.3, 7.53, 7.11	7.3
Anthony	1	0.75, 0.72, 0.64	0.70	6.87, 6.96, 7.13	6.99	5.91, 6.67, 6.52	6.4
	2						
	3	1.31, 1.08, 0.91	1.10	6.87, 8.02, 6.85	7.25	5.20, 5.74, 6.34	5.8
Brazito	1	0.50, 0.45, 0.43	0.46	7.30, 7.30, 7.37	7.32	4.30, 4.38, 4.48	4.4
	2						
	3	0.42, 0.40, 0.45	0.42	7.30, 7.46, 7.38	7.38	1.23, 1.24, 0.91	1.1

1) Local water. 2) Gypsum in local water. 3) Gypsum water.

Table 9. Continued

Soil Series	Water Type	EC_e	$\bar{x}$	pH_e	$\bar{x}$	SAR	$\bar{x}$
Casa Grande SL	1	1.95, 1.51	1.73	6.54, 6.06	6.30	6.94, 6.37	6.7
	2	1.96, 1.96	1.96	6.88, 6.77	6.83	3.44, 3.40	3.4
	3	1.32, 1.21	1.27	6.71, 6.71	6.71	2.28, 2.41	2.3
Casa Grande SCL	1	2.13, 2.31	2.22	6.23, 6.35	6.29	5.10, 6.10	5.60
	2	2.40, 2.43	2.42	6.54, 6.29	6.42	4.68, 4.22	4.5
	3	1.99, 2.00	2.00	6.58, 6.92	6.75	3.17, 3.33	3.3
Superstition	1	1.05, 0.95	1.00	6.83, 6.67	6.75	4.90, 4.55	4.73
	2	1.22, 1.36	1.29	6.44, 6.58	6.51	2.48, 2.78	2.63
	3	0.92, 0.84	0.88	6.44, 7.04	6.74	1.39, 1.54	1.47
Gadsen	1	1.26, 1.37	1.32	6.62, 6.63	6.63	5.89, 5.95	5.9
	2	1.48, 1.58	1.53	6.92, 6.60	6.76	5.48, 5.12	5.3
	3	1.20, 1.27	1.24	6.62, 6.60	6.61	4.08, 4.58	4.3

1) Local water. 2) Gypsum in local water. 3) Gypsum water.

Table 10. **The classification of local water quality data evaluate using EC_w and SAR_w Together (U.S. Salinity Laboratory, Handbook 60, 1954).**

Soil Series	EC_w	pH_w	SAR_w	Salinity and sodium classification
Gila	0.22	7.08	1.14	C 1-S 1
Pima	0.28	7.04	1.41	C 2-S 1
Vinton	0.36	7.38	4.61	C 2-S 1
Grabe	0.41	7.35	4.51	C 2-S 1
Anthony	0.57	7.17	4.45	C 2-S 1
Brazito	0.67	7.63	1.91	C 2-S 1
Casa Grande, SL	1.01	7.10	8.82	C 3-S 2
Gypsum local water	1.68		3.52	C 3-S 1
Casa Grande, SCL	1.10	7.12	9.74	C 3-S 2
Gypsum local water	1.71		3.59	C 3-S 1
Superstition	0.43	7.65	4.32	C 2-S 1
Gypsum local water	0.99		1.19	C 2-S 1
Gadsen	0.43	7.65	4.32	C 2-S 1
Gypsum local water	0.99		1.91	C 2-S 1
0.005M Ca^{2+} solution	0.68	7.19	0.02	C 2-S 1

Salinity classification	Sodium classification
C1 - Low-salinity water can be used for irrigation with most crops most soils, with little likelihood that a salinity problem will develop. Some leaching is required, but this occurs under normal irrigation practices except in soils of extremely low permeability.	S1 - Low-sodium water can be used for irrigation on almost all soils with little danger of the development of a sodium problem. However, sodium-sensitive crop, such as stone-fruit and avocados, may accumulate injurious amounts of sodium in the leaves.
C2 - Medium-salinity water can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most instances without special practices for salinity control.	S2 - Medium-sodium water may present a moderate sodium problem in fine-textured (clay) soils unless there is gypsum in the soil. This water can be used on coarse-textured (sandy) or organic soils that take water well.
C3 - High-salinity water cannot be used on soil with restricted drainage. Even with adequate drainage, special management for salinity control may be required, and plants with good salt tolerance should be selected.	S3 - High-sodium water may produce troublesome sodium problems in most soils and will require special management, good drainage, high leaching, and additions of organic matter. If there is plenty of gypsum in the soil a serious problem may not present, it or some similar material may have to be added.
C4 - Very-high- salinity water in not suitable for irrigation under ordinary conditions but may be used occasionally under very special circumstances. The soil must be permeable, drainage must be adequate, irrigation water must be applied in excess to provide considerable leaching, and vary-slat tolerant crops should be selected.	S4 - Very-high-sodium water is generally unsatisfactory for irrigation except at low- or medium-salinity levels, where the use of gypsum or some other amendment makes it possible to use such water.

Table 11. "None-dispersed" particle-size and aggregate stability data for the < 2 mm soil fraction.

Soil Series	Horizon	The < 2 mm soil fraction by hand sieving "Soil Quality Test Kit"						The < 2 mm soil fraction by the machine sieving at a frequency of 35 cycles/min				
		None-dispersed particle-size on*			Aggregate stability on*			None-dispersed particle-size on*		Aggregate stability on*		
		0.3 mm sieve	0.075 mm sieve	0.25 mm sieve	0.3 mm sieve	0.075 mm sieve	0.25 mm sieve	0.3 mm sieve	0.075 mm sieve	0.3 mm sieve	0.075 mm sieve	0.5** mm sieve
Gila	Ap	43.48	78.57	51	39.03	62.50	45.68	28.30	82.52	22.65	69.41	4.00
Pima	Ap	52.17	78.57	58	49.68	74.94	55.32	25.43	67.99	21.55	62.56	7.00
Vinton	Ap	13.04	35.71	39	8.22	28.88	33.19	10.32	69.99	5.35	38.63	2.00
Grabe	Ap	43.48	78.57	57	40.57	66.59	53.36	16.58	76.25	12.28	62.98	5.00
Anthony	Ap	30.43	78.57	45	22.74	52.64	34.91	15.41	73.08	6.06	40.51	18.0
Brazito	Ap	52.17	92.86	67	47.44	19.14	59.92	13.00	93.00	4.40	20.72	0.00
Casa Grande SL	Ap	52.17	92.86	63	34.43	81.33	42.01	35.68	84.67	11.83	59.92	0.00
Casa Grande SCL	Ap	69.57	100.00	74	60.84	100.00	62.54	34.62	84.78	15.86	65.45	5.00
Superstition	Ap	52.17	85.71	54	37.84	33.22	27.22	35.41	95.17	16.06	77.43	40.0
Gadsen	Ap	8.70	92.86	52	8.54	92.29	51.85	26.39	70.34	26.26	67.98	7.00

* None-dispersed particle-size is the total percentage of soil retain in the sieve, whereas aggregate stability is the percentage after subtracting the percent sand in that sample.

** Completed by national Soil Survey Laboratory

Table 12. Volumetric water content measured on undisturbed soil cores.

Soil series	Volumetric water content at			
	1 kPa	33 kPa	100 kPa	1500 kPa
Gila	0.2492	0.2064	0.1803	0.1458
Pima	0.3522	0.3275	0.3082	0.2814
Vinton	0.2083	0.1637	0.1386	0.1098
Grabe	0.3155	0.2750	0.2513	0.2230
Anthony	0.2644	0.2291	0.2046	0.1671
Brazito	0.1356	0.0661	0.0503	0.0448
Casa Grande SL	0.2338	0.1860	0.1600	0.1311
Casa Grande SCL	0.2764	0.2292	0.2033	0.1744
Superstition	0.1500	0.1080	0.0885	0.0720
Gadsen	0.4411	0.4219	0.4006	0.3650

Table 13. Pearson correlations (r), R^2, and best curve estimations between soil properties estimated in field by soil scientists and K_{sat} of ten soils.

Independent variables (x)	Dependent variable K_{sat} (y)		
	Best curve estimation	R^2	r
% Clay estimations	$y = 27.997x^{-1.2112}$	0.7402	-0.464**
% Sand estimations	$y = 0.1463e^{0.0392x}$	0.5374	0.542**
Stickness	$y = 1.3294x^{-1.0691}$	0.7181	-0.556**
Plasticity	$y = 1.5987x^{-1.1394}$	0.8096	-0.571**
Effervescence	$y = 53.087e^{-1.2373x}$	0.6825	-0.978**
Bulk Density (g cm^{-3})	$y = 13.362x^{-5.3014}$	0.0562	-0.345**
Rating of Bulk Density	$y = 12.755x^{-3.8237}$	0.5956	-0.651**
None-dispersed particle-size on 0.075 mm sieves	$y = 0.1003x - 2.307$	0.0163	0.128
None-dispersed particle-size on 0.25 mm sieves	$y = 0.4209x - 17.711$	0.0954	0.309**
None-dispersed particle-size on 0.3 mm sieves	$y = 0.1038x + 1.5278$	0.0198	0.141
% Aggregate Stability on 0.075 mm sieves	$y = 31966x^{-2.5387}$	0.7185	-0.598**
% Aggregate Stability on 0.25 mm sieves	$y = 44.258x^{-0.9353}$	0.0251	0.321**
% Aggregate Stability on 0.3 mm sieves	$y = 1.9097x^{-0.1241}$	0.0029	0.191

* Significantly different at the 95% confidence level.
** Significantly different at the 99% confidence level.

Table 14. Pearson correlations (r), R^2, and best curve estimations between soil properties estimated in field by soil Scientists and K_{sat} of nine soils (Brazito soil excluded).

Independent variables (x)	Dependent variable K_{sat} (y)		
	Best curve estimation	R^2	r
% Clay estimations	$y = 12.1x^{-0.9354}$	0.4337	-0.507**
% Sand estimations	$y = 0.2397e^{0.0251x}$	0.4058	0.512**
Stickness	$y = 3.2303e^{-0.7349x}$	0.4507	-0.542**
Plasticity	$y =- 1.7921Ln(x)+2.483$	0.4473	-0.621**
Effervescence	$y = 4076.2x^{-7.0152}$	0.2911	-0.620**
Bulk Density (g cm^{-3})	$y = -0.8225x+2.7632$	0.0028	-0.053
Rating of Bulk Density	$y = 7.1031e^{-1.0481x}$	0.2103	-0.456**
None-dispersed particle-size on 0.075 mm sieves	$y = -5.024ln(x)+23.32$	0.698	-0.789**
None-dispersed particle-size on 0.25 mm sieves	$y = 469061x^{-3.3171}$	0.3016	-0.552**
None-dispersed particle-size on 0.3 mm sieves	$y = -0.0383x+3.0192$	0.1717	-0.414**
% Aggregate Stability on 0.075 mm sieves	$y = 1472x^{-1.8154}$	0.4927	-0.630**
% Aggregate Stability on 0.25 mm sieves	$y = 20.501e^{-0.0707x}$	0.5475	0.576**
% Aggregate Stability on 0.3 mm sieves	$y =-1.3487Ln(x)+5.9498$	0.2893	-0.519**

* Significantly different at the 95% confidence level.
** Significantly different at the 99% confidence level.

Table 15. Beta (β) values of each soil properties were estimated by soil scientists (independent variables) and the subset provided from each run, R^2, R^2_{adj}, and C_p.

Independent variables	Beta (β) value of predictor variables				
	Run 1	Run 2*	Run 3	Run 4**	Run 5***
Constant	1.003	-89.749	63.514	-353.158	6.841
% Clay estimations				-2.520	0.003385
% Sand estimations		0.173		0.324	0.126
Stickness					0.923
Plasticity			-5.785	11.823	
Effervescence	-14.056				
Bulk Density (g cm^{-3})	28.243	31.933	-29.787	171.083	-9.572
Rating of Bulk Density					4.718
None-dispersed particle-size on 0.075 mm sieves	0.123	0.377		1.046	-0.107
None-dispersed particle-size on 0.25 mm sieves		-1.214		-1.595	
None-dispersed particle-size on 0.3 mm sieves	-0.280	1.697			
% Aggregate Stability on 0.075 mm sieves		-0.535			
% Aggregate Stability on 0.25 mm sieves		2.366		3.747	
% Aggregate Stability on 0.3 mm sieves	0.138	-2.148		-1.985	
R^2	0.992	0.994	0.388	0.997	0.884
R^2_{adj}	0.991	0.993	0.366	0.994	0.870
C_p	18.705	8.071	3.997	9.000	7.000

* Model A
** Model B
*** Model C (Brazito soil excluded)

Table 16. Comparison of measured and predicted hydraulic conductivity (cm/hr) using subsets soil properties were estimated by soil scientists.

Soil Series	Water Type	Measured mean K_{sat} (cm/hr)	Predicted Value of models				
			Run 1	Run 2*	Run 3	Run 4**	Run 5***
Gila	1	1.11	0.00874	0.7143	11.5613	1.0100	0.7197
	3	0.47	0.00874	0.7143	11.5613	1.0100	0.7197
Pima	1	0.27	0.7782	0.4124	-10.6890	0.4958	0.3957
	3	0.56	0.7782	0.4124	-10.6890	0.4958	0.3957
Vinton	1	6.82	5.6109	5.7700	14.2372	5.7472	5.7809
	3	4.73	5.6109	5.7700	14.2372	5.7472	5.7809
Grabe	1	0.53	0.5038	0.4788	5.0156	0.3628	0.5117
	3	0.42	0.5038	0.4788	5.0156	0.3628	0.5117
Anthony	1	1.07	2.8191	1.4118	8.7414	1.2298	1.3534
	3	1.59	2.8191	1.4118	8.7414	1.2298	1.3534
Brazito	1	43.37	45.3304	45.4011	20.0333	45.3949	NA
	3	47.43	45.3304	45.4011	20.0333	45.3949	NA
Casa Grande SL	1	1.18	2.0887	1.9872	4.0530	2.2807	1.9574
	2	2.44	2.0887	1.9872	4.0530	2.2807	1.9574
	3	2.43	2.0887	1.9872	4.0530	2.2807	1.9574
Casa Grande SCL	1	0.26	0.6193	0.4822	-0.8298	0.2933	0.4897
	2	0.89	0.6193	0.4822	-0.8298	0.2933	0.4897
	3	0.17	0.6193	0.4822	-0.8298	0.2933	0.4897
Superstition	1	1.78	0.8591	1.5902	7.6175	1.4661	1.6281
	2	1.65	0.8591	1.5902	7.6175	1.4661	1.6281
	3	1.39	0.8591	1.5902	7.6175	1.4661	1.6281
Gadsen	1	0.24	-0.0343	0.3299	-1.1571	0.3028	0.3450
	2	0.45	-0.0343	0.3299	-1.1571	0.3028	0.3450
	3	0.35	-0.0343	0.3299	-1.1571	0.3028	0.3450

1) Local water. 2) Gypsum in local water. 3) Gypsum water.
NA Not Applicable.
* Model A
** Model B
*** Model C (Brazito soil excluded)

Table 17. Pearson correlations (r), R^2, and best curve estimations between soil properties measured in the laboratory analyses and K_{sat} of ten soils.

Independent variables (x)	Dependent variable K_{sat} (y)		
	Best curve estimation	R^2	r
% Clay measurements	$y = 20.241x^{-1.166}$	0.7878	-0.471**
% Silt measurements	$y = 19.196x^{0.9673}$	0.6434	-0.596**
% Sand measurements	$y = 0.0959e^{0.0446x}$	0.5424	0.576**
% Very fine sand measurements	$y = 0.124x + 3.8804$	0.0036	0.060
% Fine sand measurements	$y = 0.1662e^{0.0813x}$	0.7625	0.844**
% Medium sand measurements	$y = 0.4297x + 1.091$	0.0699	0.264*
% Coarse sand measurements	$y = -1.7036\ln(x) + 6.6794$	0.0648	-0.320**
% Very coarse sand measurements	$y = 1.0148x^{-0.3039}$	0.1945	-0.295*
Bulk Density ($g\ cm^{-3}$)	$y = 13.362x^{-5.3014}$	0.0562	-0.345**
Rating of Bulk Density	$y = 12.755x^{-3.8237}$	0.5956	-0.651**
None-dispersed particle-size on 0.075 mm sieves	$y = 3E^{-11}x^{5.6017}$	0.1689	0.460**
None-dispersed particle-size on 0.3 mm sieves	$y = 521.46x^{-1.956}$	0.2864	-0.449**
Aggregate Stability on 0.075 mm sieves	$y = 830959x^{-3.3718}$	0.6774	-0.763**
Aggregate Stability on 0.3 mm sieves	$y = 184.33x^{-2.0005}$	0.6005	-0.514**
Aggregate Stability on 0.5 mm sieves	$y = 1.0368e^{0.019x}$	0.0185	0.067
Soil Ec_e	$y = 1.3124x^{-2.1522}$	0.3536	-0.474**
Soil SAR_e	$y = 8.4124x^{-1.2683}$	0.1693	-0.391**
Water EC_w	$y = -1.2692x + 6.7444$	0.0011	-0.033
Water SAR_w	$y = -0.748x + 7.454$	0.0215	-0.147
Soil CO_3	$y = 4.371e^{-0.2901}$	0.3878	-0.474**
Volumetric water content at 1 kPa	$y = 0.0025x^{-4.6755}$	0.7617	-0.640**
Volumetric water content at 33 kPa	$y = 0.0121x^{-2.9944}$	0.7903	-0.662**
Volumetric water content at 100 kPa	$y = 0.0148x^{-2.6344}$	0.7886	-0.623**
Volumetric water content at 1500 kPa	$y = 0.0121x^{-2.5109}$	0.7752	-0.555**
1500 kPa: Clay ratio	$y = 0.327x^{-1.7338}$	0.3313	-0.693**

* Significantly different at the 95% confidence level.
** Significantly different at the 99% confidence level.

Table 18. Pearson correlations (r), R^2, and best curve estimations between soil properties measured in the laboratory analyses and K_{sat} of nine soils (Brazito soil excluded).

Independent variables (x)	Dependent variable K_{sat} (y)		
	Best curve estimation	R^2	r
% Clay measurements	$y = 20.37x^{-1.1683}$	0.4858	-0.495**
% Silt measurements	$y = 2.5743e^{-0.0393x}$	0.2264	-0.327**
% Sand measurements	$y = 0.1936e^{0.0277x}$	0.363	0.449**
% Very fine sand measurements	$y = 0.1508x - 0.9445$	0.348	0.590**
% Fine sand measurements	$y = 0.2093e^{0.0685x}$	0.4483	0.564**
% Medium sand measurements	$y = 0.5518e^{0.0408x}$	0.1039	0.104
% Coarse sand measurements	$y = 0.7642x^{0.1484}$	0.0804	-0.056
% Very coarse sand measurements	$y = -0.0556x + 1.5673$	0.0038	-0.062
Bulk Density (g cm^{-3})	$y = -0.8225x + 2.7632$	0.0028	-0.053
Rating of Bulk Density	$y = 3.878x^{-2.2267}$	0.2116	-0.456**
None-dispersed particle-size on 0.075 mm sieves	$y = -0.0259x + 3.4902$	0.0163	-0.128
None-dispersed particle-size on 0.3 mm sieves	$y = -2.3553Ln(x) + 8.901$	0.3151	-0.439**
Aggregate Stability on 0.075 mm sieves	$y = -4.8431Ln(x) + 21.223$	0.4021	-0.600**
Aggregate Stability on 0.3 mm sieves	$y = 25.035x^{-1.301}$	0.4234	0.611**
Aggregate Stability on 0.5 mm sieves	$y = 0.7602e^{0.0106x}$	0.0138	-0.09
Soil Ec_e	$y = -0.7693x + 2.3841$	0.0434	-0.208
Soil SAR_e	$y = 0.1082x + 0.9007$	0.0119	0.109
Water EC_w	$y = -0.3501Ln(x) + 1.2976$	0.0102	-0.084
Water SAR_w	$y = 0.036x + 1.3833$	0.0032	0.056
Soil CO_3	$y = 1.8815e^{-0.168x}$	0.2577	-0.449**
Volumetric water content at 1 kPa	$y = 0.0092x^{-3.5878}$	0.5112	-0.587**
Volumetric water content at 33 kPa	$y = 0.017x^{-2.7427}$	0.4979	-0.558**
Volumetric water content at 100 kPa	$y = 0.0219x^{-2.3688}$	0.4969	-0.543**
Volumetric water content at 1500 kPa	$y = 0.0265x^{-2.022}$	0.5059	-0.553**
1500 kPa: Clay ratio	$y = 8.7928x - 3.3909$	0.3907	0.625**

* Significantly different at the 95% confidence level.
** Significantly different at the 99% confidence level.

Table 19. Beta (β) value of each of soil properties were measured in the laboratory analyses (independent variables) and the subset provided from each run, R^2, R^2_{adj}, and C_p.

Independent variables	Beta (β) of predictor variables		
	Run 1*	Run 2**	Run 3***
Constant	8.002	3.007	-20.540
% Clay measurements	0.593	0.728	0.600
% Silt measurements			-0.202
% Sand measurements	-0.800	-0.800	
% Very fine sand measurements			1.002
% Fine sand measurements	1.704	1.866	
% Medium sand measurements			
% Coarse sand measurements			
% Very coarse sand measurements	1.402	1.610	0.881
Bulk Density (g cm^{-3})			
Rating of Bulk Density			5.755
None-dispersed particle-size on 0.075 mm sieves			
None-dispersed particle-size on 0.3 mm sieves			
Aggregate Stability on 0.075 mm sieves	0.0860	0.245	
Aggregate Stability on 0.3 mm sieves			
Aggregate Stability on 0.5 mm sieves			0.07787
Soil Ec_e****			
Soil SAR_e****	-0.819		
Soil CO_3****			
Water EC_w****			
Water SAR_w****	0.231		
Volumetric water content at 1 kPa	109.136		-46.550
Volumetric water content at 33 kPa			
Volumetric water content at 100 kPa	-202.466	-125.789	
Volumetric water content at 1500 kPa			
1500 kPa: Clay ratio			
R^2	0.995	0.997	0.882
R^2_{adj}	0.994	0.994	0.864
C_p	10.599	4.074	8.272

* Model D

** Model E

*** Model F (Brazito soil excluded)

**** excluded from Run 2

Table 20. Comparison of measured and predicted hydraulic conductivity (cm/hr) using subsets soil Properties were measured in the laboratory analyses.

Soil Series	Water Type	Measured mean K_{sat} (cm/hr)	Predicted Value of models		
			Run 1*	Run 2**	Run 3***
Gila	1	1.11	0.7434	0.8256	0.8607
	3	0.47	0.9763	0.8256	0.8607
Pima	1	0.27	0.1109	0.4295	0.4618
	3	0.56	0.2814	0.4295	0.4618
Vinton	1	6.82	6.1366	5.7988	5.7900
	3	4.73	5.4865	5.8001	5.7900
Grabe	1	0.53	0.9778	0.3708	0.4471
	3	0.42	0.1870	0.3708	0.4471
Anthony	1	1.07	1.5288	1.3334	1.0981
	3	1.59	0.9975	1.3334	1.0981
Brazito	1	43.37	44.2656	45.3968	NA
	3	47.43	46.5320	45.3968	NA
Casa Grande SL	1	1.18	1.0515	2.0274	1.9542
	2	2.44	2.5307	2.0274	1.9542
	3	2.43	2.6237	2.0274	1.9542
Casa Grande SCL	1	0.26	0.7540	0.3981	0.5663
	2	0.89	0.2352	0.3981	0.5663
	3	0.17	0.3939	0.3981	0.5663
Superstition	1	1.78	0.6070	1.6281	1.6816
	2	1.65	1.6044	1.6281	1.6816
	3	1.39	2.2843	1.6281	1.6816
Gadsen	1	0.24	0.4143	0.3748	0.3220
	2	0.45	0.1832	0.3748	0.3220
	3	0.35	0.7321	0.3748	0.3220

1) Local water. 2) Gypsum in local water. 3) Gypsum water.

NA Not Applicable.

* Model D

** Model E

*** Model F (Brazito soil excluded)

Table 21. Collinearity diagnostics of subset of adequate models with soil properties were estimated by soil scientists.

Independent variables	Eigenvalue value of predictor variables		
	Mode A	Model B	Model C*
Constant	8.386	7.995	6.270
% Clay estimations		0.03153	0.02239
% Sand estimations	0.0001821	0.00005027	0.054
Stickness			0.0003564
Plasticity		0.784	
Effervescence			
Bulk Density (g cm^{-3})	0.0004423	0.02421	0.00435
Rating of Bulk Density			0.01998
None-dispersed particle-size on 0.075 mm sieves	0.04401	0.004796	0.629
None-dispersed particle-size on 0.25 mm sieves	0.002603	0.001649	
None-dispersed particle-size on 0.3 mm sieves	0.01717		
Aggregate Stability on 0.075 mm sieves	0.189		
Aggregate Stability on 0.25 mm sieves	0.329	0.146	
Aggregate Stability on 0.3 mm sieves	0.0305	0.0126	

* (Brazito soil excluded)

Table 22. Collinearity diagnostics of subset of adequate models with soil properties were measured by laboratory analyses.

Independent variables	Eigenvalue value of predictor variables		
	Model D	Model E	Model F*
Constant	7.702	5.404	6.256
% Clay measurements	0.08806	0.008755	0.350
% Silt measurements			0.006307
% Sand measurements	0.699	0.559	
% Very fine sand measurements			0.765
% Fine sand measurements	0.998	0.951	
% Medium sand measurements			
% Coarse sand measurements			
% Very coarse sand measurements	0.07120	0.003703	0.001524
Bulk Density (g cm^{-3})			
Rating of Bulk Density			0.03491
None-dispersed particle-size on 0.075 mm sieves			
None-dispersed particle-size on 0.3 mm sieves			
Aggregate Stability on 0.075 mm sieves	0.004026	0.001614	
Aggregate Stability on 0.3 mm sieves			
Aggregate Stability on 0.5 mm sieves			0.0002554
Soil Ec_e			
Soil SAR_e	0.002820		
Water EC_w			
Water SAR_w	0.0001235		
Soil CO_3			
Volumetric water content at 1 kPa	0.001398		0.586
Volumetric water content at 33 kPa			
Volumetric water content at 100 kPa	0.433	0.07109	
Volumetric water content at 1500 kPa			
1500 kPa: Clay ratio			

* (Brazito soil excluded)

Table 23. **Paired Samples T Test for mean predicted K_{sat} from mean models against measured mean data of field-saturated hydraulic conductivity.**

	Paired difference at 99 % confidence interval of the difference			
	Standard error of mean	T	df	Significant (2- tailed)
Measured K_{sat} vs. predicted K_{sat} from model A	0.1373	-0.02	59	0.983
Measured K_{sat} vs. predicted K_{sat} from model B	0.1384	-0.025	59	0.980
Measured K_{sat} vs. predicted K_{sat} from model C*	0.009526	0.000	53	1.000
Measured K_{sat} vs. predicted K_{sat} from model D	0.1177	-0.30	59	0.976
Measured K_{sat} vs. predicted K_{sat} from model E	0.1373	-0.026	59	0.980
Measured K_{sat} vs. predicted K_{sat} from model F*	0.008063	0.000	53	1.000

* (Brazito soil excluded)

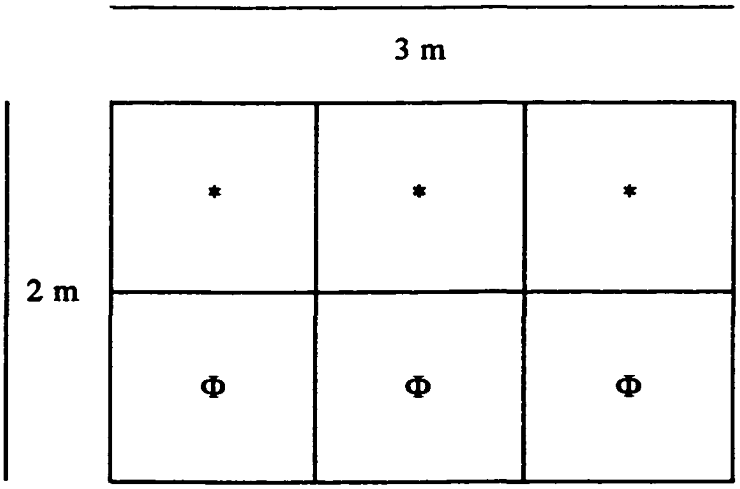
Table 24. Comparison of predicted K_{sat} using new proposed models and predicted K_{sat} using Rosetta model*

Soil Series	Measured K_{sat} (cm/hr) $\bar{x}$	Predicted K_{sat} using new proposed models (cm/hr)						Predicted K_{sat} using Rosetta model* (cm/hr)				
		Model A	Model B	Model C	Mode 1D	Model E	Model F	Model 1	Model 2	Model 3	Model 4	Model 5
Gila	0.7883	0.7143	1.0100	0.7197	NA	0.8256	0.8607	1.5936	1.4197	1.3583	1.4122	2.0888
Pima	0.4150	0.4124	0.4958	0.3957	NA	0.4295	0.4618	0.4006	0.5134	0.0552	0.0358	0.0270
Vinton	5.7717	5.7700	5.7472	5.7809	NA	5.7988	5.7900	1.5936	2.2698	2.1498	2.0606	2.6229
Grabe	0.4750	0.4788	0.3628	0.5117	NA	0.3708	0.4471	0.5015	0.4587	0.5138	0.8181	1.0275
Anthony	1.3267	1.4118	1.2298	1.3534	NA	1.3334	1.0981	1.5936	1.6289	1.5261	0.5317	0.9128
Brazito	45.3667	45.401	45.395	NA	NA	45.397	NA	26.791	52.758	59.496	36.965	35.147
Casa Grande SL	2.0167	1.9872	2.2807	1.9574	NA	2.0274	1.9542	1.5936	1.3539	1.0344	1.4665	1.6580
Casa Grande SCL	0.4400	0.4822	0.2933	0.4897	NA	0.3981	0.5663	0.5495	0.7762	0.7580	1.1094	1.2373
Superstition	1.6033	1.5902	1.4661	1.6281	NA	1.6281	1.6816	4.3801	7.6276	3.6525	4.4350	4.5697
Gadsen	0.3450	0.3299	0.3028	0.3450	NA	0.3748	0.3220	0.4006	0.6636	0.2419	0.1239	0.1018
$\bar{x}$ of ten soils	5.8548	5.8578	5.8584		NA	5.8584		3.9398	6.9470	7.0786	4.8958	4.9393
$\bar{x}$ of nine soils**	1.46463			1.46462			1.46464					

* Basic soil data are used by hierarchical artificial neural network models (ANN) which allow five levels (models) of input:
Model 1 (TXT) prediction is based on class average values of the hydraulic parameters
Model 2 (SSC) sand, silt and clay percentages are used
Model 3 (SSCBD) sand, silt and clay percentages and bulk density
Model 4 (SSCBDTH33) sand, silt and clay percentages, bulk density and the water content at 33 kPa (330 cm. 0.33 atm)
Model 5 (SSCBDTH331500) sand, silt and clay percentages, bulk density and the water content at 33 and 1500 kPa
NA Not Applicable.
** Brazito soil excluded.

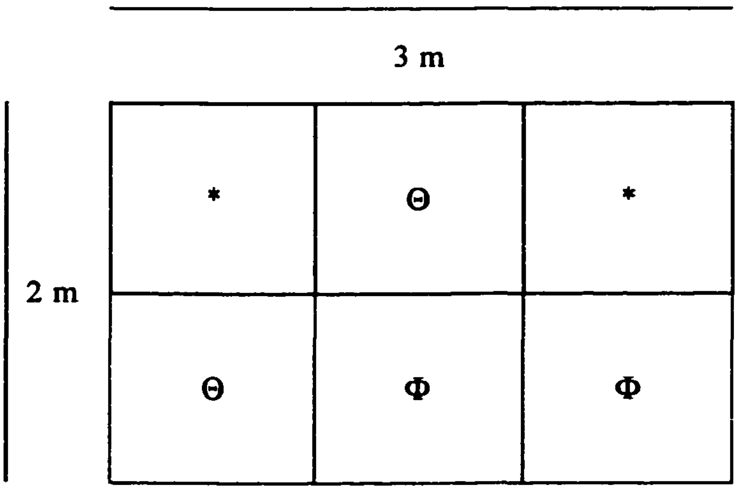
FIGURE CAPTIONS

Figure 1. Plot locations for measuring K_{sat} in Gila, Pima, Vinton, Grabe, Anthony, and Brazito Soils.



ϕ Local water
* 0.005 M $CaSO_4 \cdot 2H_2O$ - 0.86 g L^{-1} in the dionized water

Figure 2. Plot locations for measuring K_{sat} Casa Grande SL, Casa Grande SCL, Superstition, and Gadsen Soils.



Φ Local water
Θ 0.86 $CaSO_4 \cdot 2H_2O$ - g L^{-1} in the local water
* 0.005 M $CaSO_4 \cdot 2H_2O$ - 0.86 g L^{-1} in the dionized water

Figure 3. Schematic of Mariotte syphon to maintain constant water level in infiltrometer.

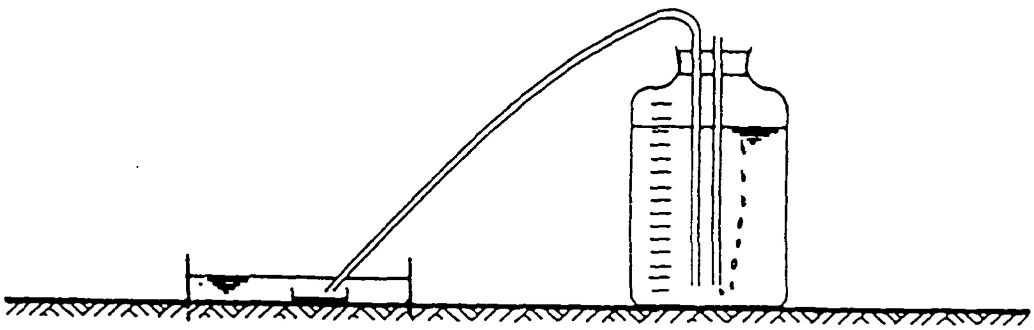


Figure 4. Schematic of tempe cell with hanging water column.

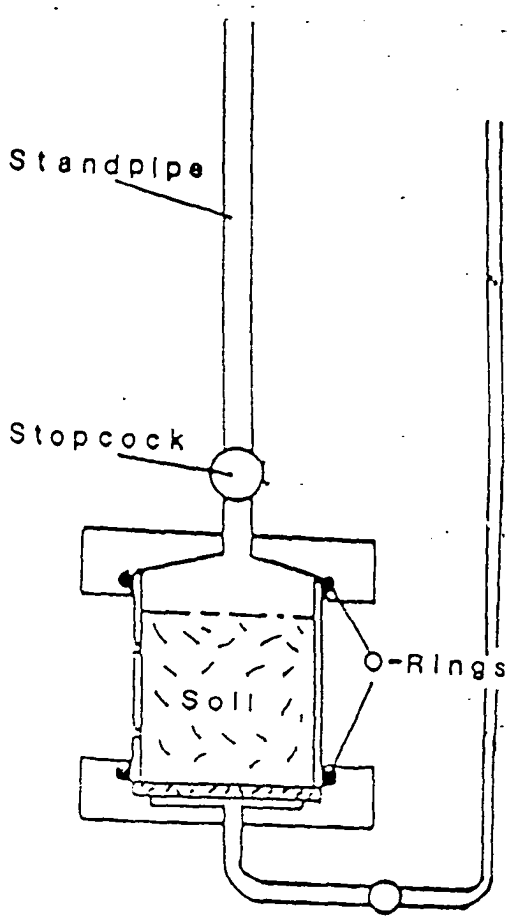


Figure 5. % Clay laboratory mesurements vs. % clay estimated by soil scientists

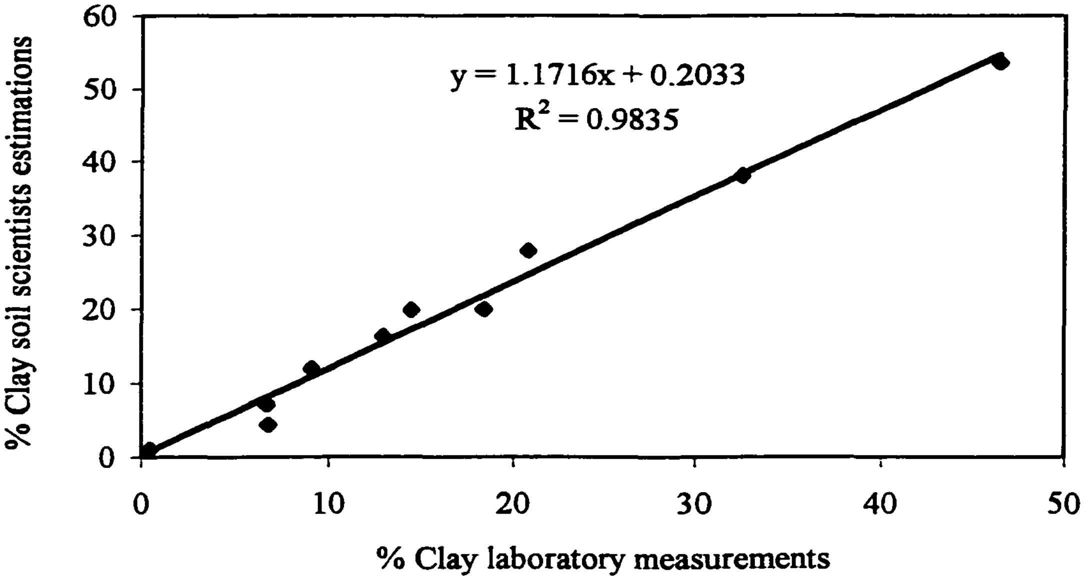


Figure 6. % Sand laboratory mesurements vs. % sand estimated by soil scientists

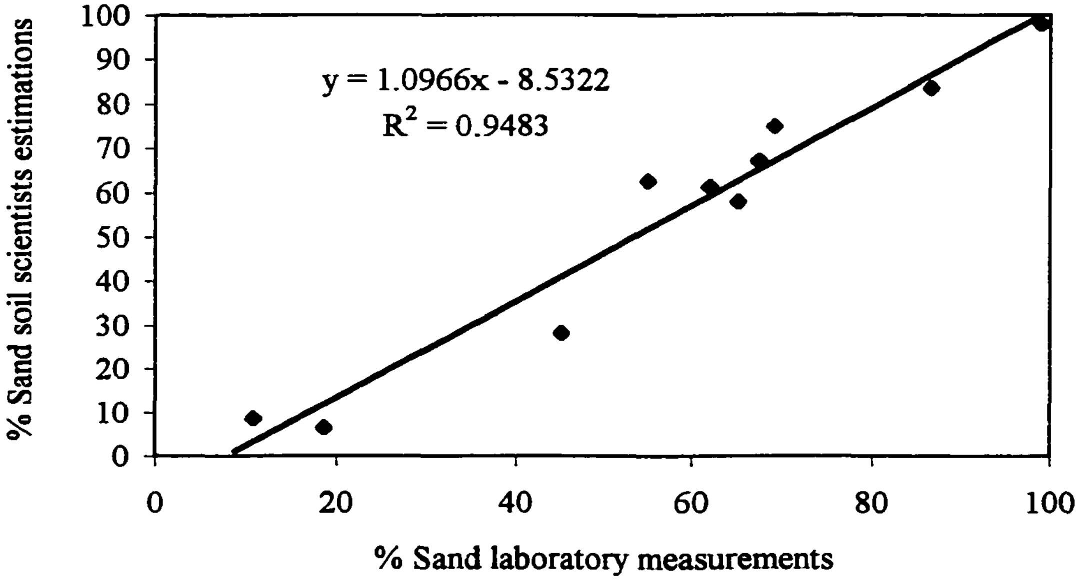


Figure 7. Predicted value of K_{sat} using Model A vs. measured value of K_{sat} for ten soils.

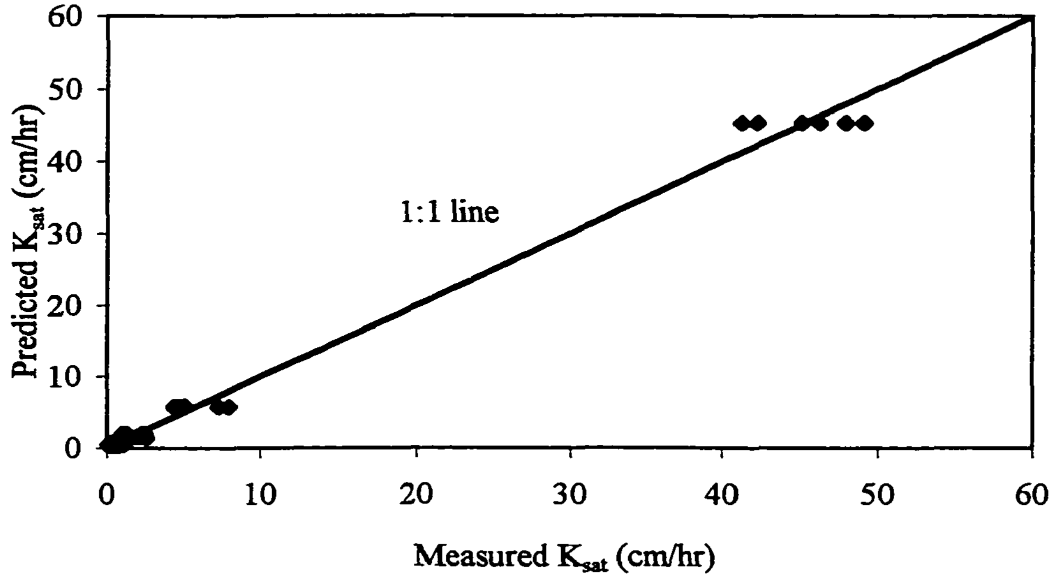


Figure 8. Predicted value of K_{sat} using Model B vs. measured value of K_{sat} for ten soils.

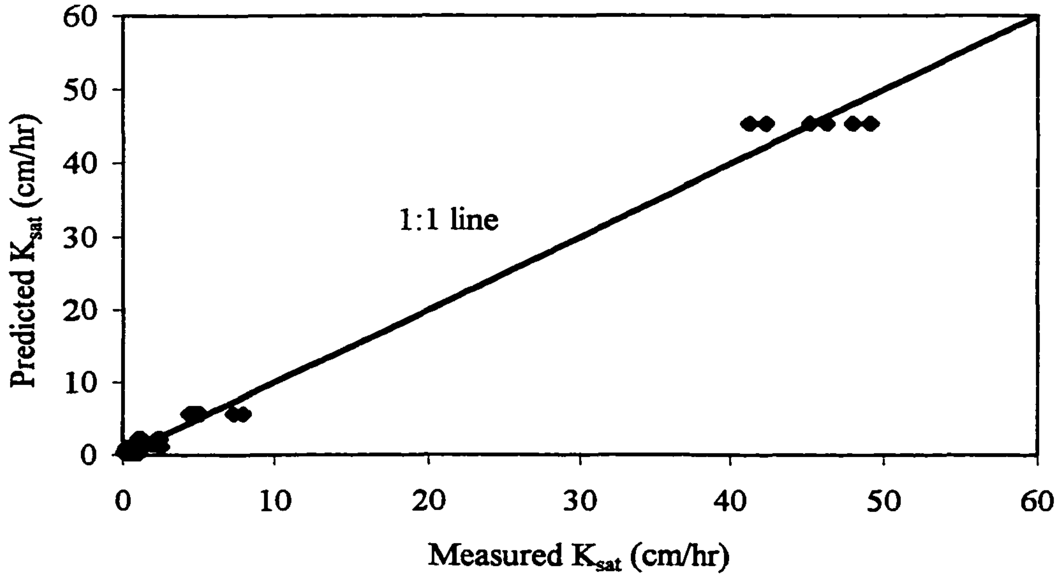


Figure 9. Predicted value of K_{sat} using Model C vs. measured value of K_{sat} for nine soils (Brazito soil excluded).

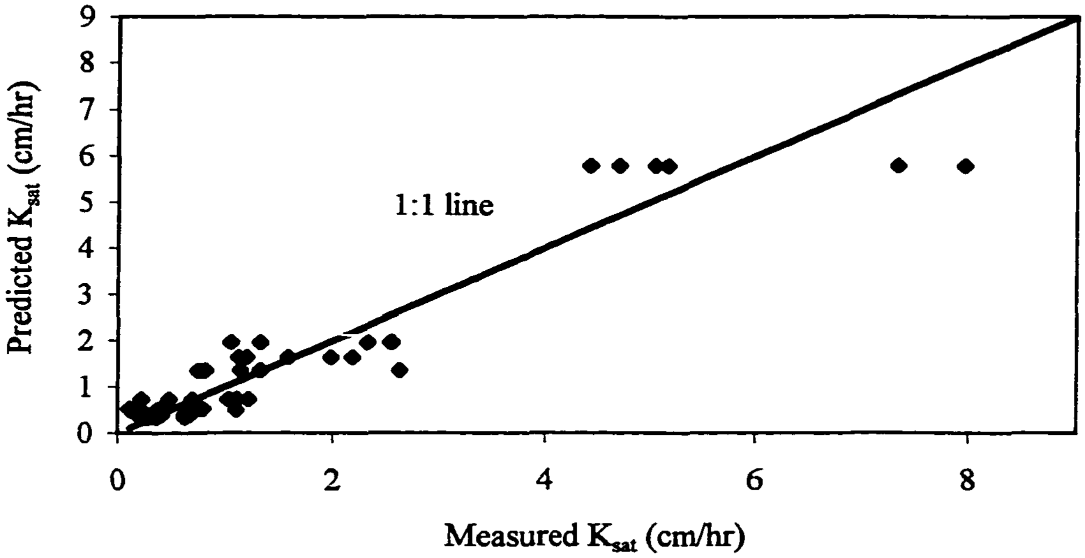


Figure 10. Predicted value of K_{sat} using Model D vs. measured value of K_{sat} for ten soils.

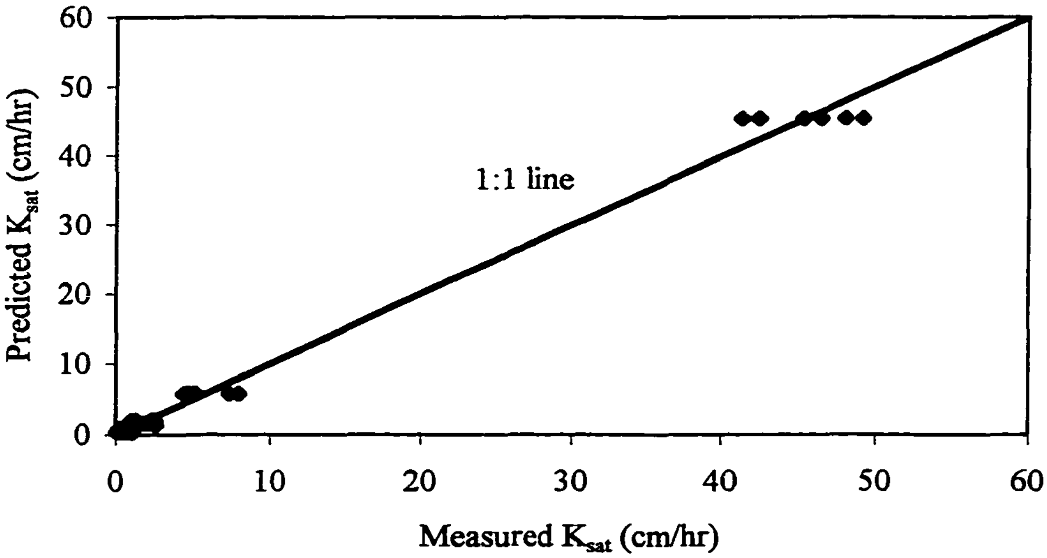


Figure 11. Predicted value of K_{sat} using Model E vs. measured value of K_{sat} for ten soils.

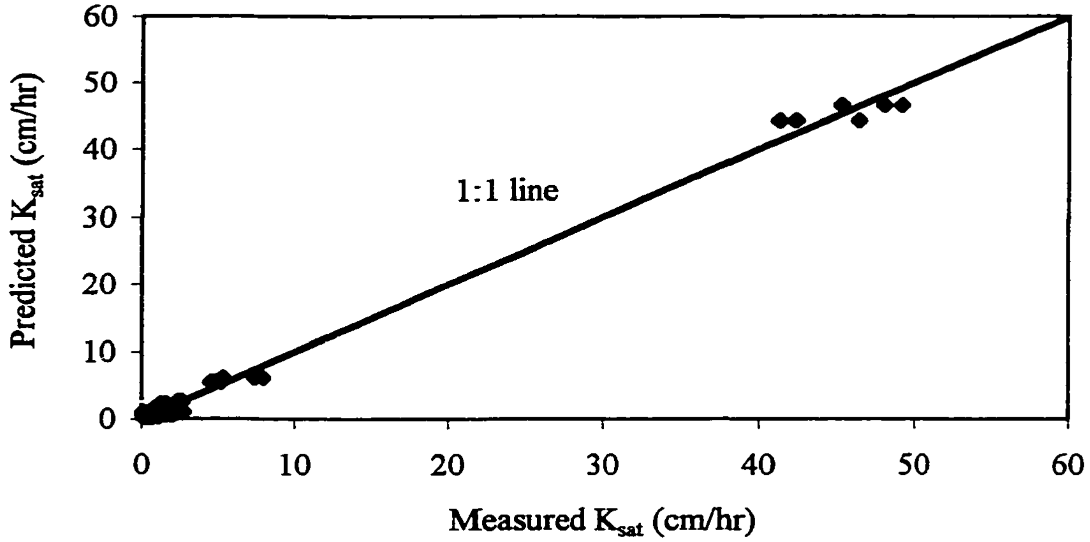


Figure 12. Predicted value of K_{sat} using Model F vs. measured value of K_{sat} for nine soils (Brazito soil excluded).

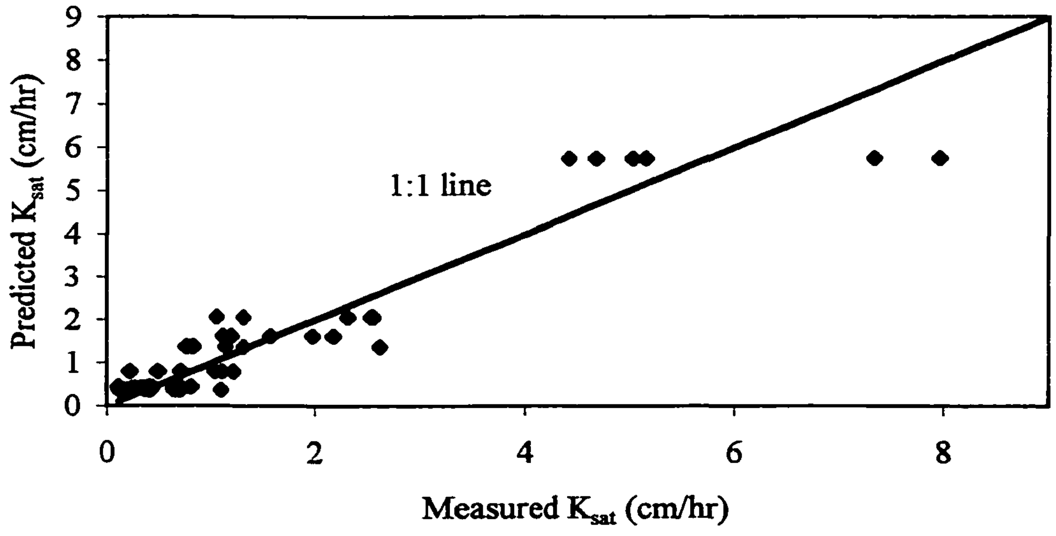


Figure 13. Predicted value of K_{sat} using Rosetta models vs. mean of measured value of K_{sat} for ten soils.

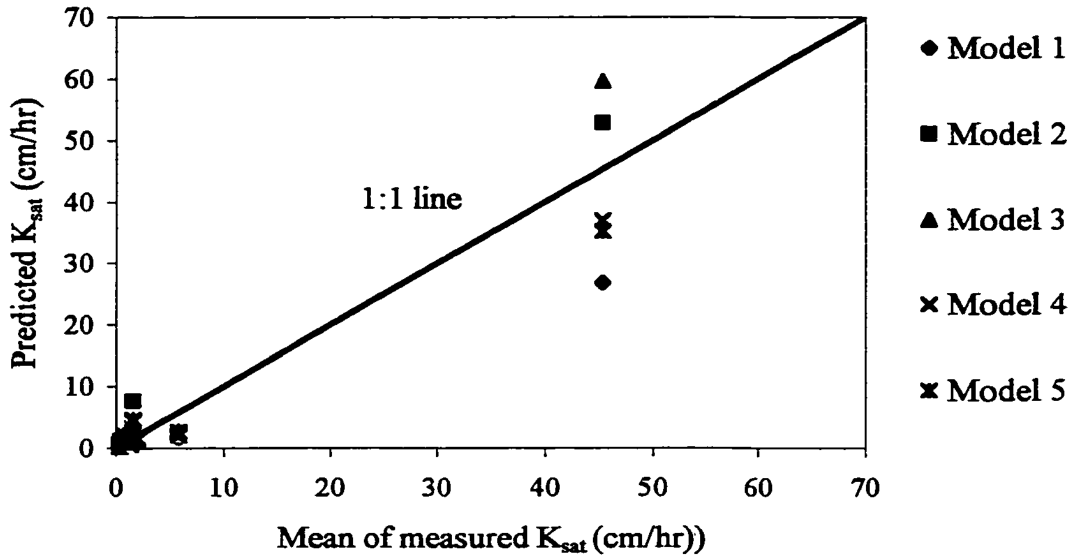
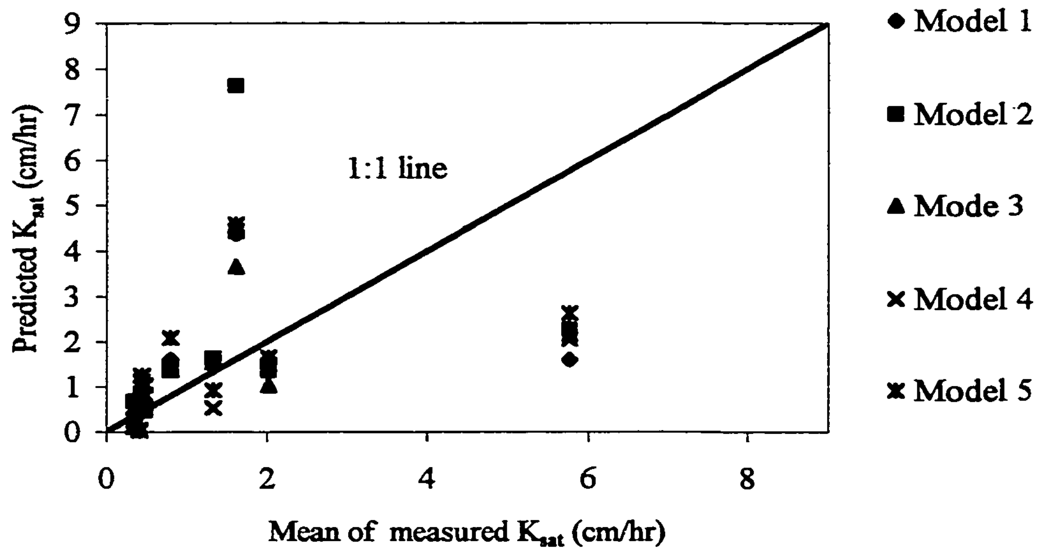


Figure 14. Predicted value of K_{sat} using Rosetta models vs. mean of measured value of K_{sat} for nine soils (Barzito soil excluded).



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Supplemental Material

Table 1. Steady State Infiltration Rates Data for Study Sites.

Soil Series	Water Type	Single Ring	$\bar{x}$	Corrected Single Ring	$\bar{x}$	Double Rings	$\bar{x}$
Gila	1	1.75, 1.80, 1.25	1.60	0.71, 0.73, 0.51	0.65	1.10, 1.21, 1.02	1.11
	2						
	3	0.96, 0.55, 0.49	0.67	0.39, 0.22, 0.20	0.27	0.70, 0.48, 0.22	0.47
Pima	1	1.00, 0.88, 0.75	0.88	0.42, 0.37, 0.31	0.37	0.19, 0.41, 0.20	0.27
	2						
	3	1.75, 2.26, 1.00	1.67	0.73, 0.94, 0.42	0.70	0.39, 0.63, 0.67	0.56
Vinton	1	8.23, 6.28, 7.71	7.41	3.33, 2.54, 3.12	3.00	7.96, 5.17, 7.32	6.82
	2						
	3	5.68, 6.13, 5.60	5.80	2.30, 2.48, 2.27	2.35	4.43, 4.70, 5.05	4.73
Grabe	1	0.34, 0.90, 0.95	0.73	0.14, 0.34, 0.38	0.29	0.11, 0.69, 0.79	0.53
	2						
	3	0.72, 0.62, 0.54	0.63	0.29, 0.25, 0.22	0.25	0.42, 0.41, 0.43	0.42
Anthony	1	1.5, 1.13, 2.07	1.57	0.61, 0.46, 0.84	0.64	1.13, 0.75, 1.32	1.07
	2						
	3	3.20, 1.50, 1.41	2.04	1.30, 0.61, 0.57	0.83	2.63, 1.32, 0.81	1.59
Brazito	1	65.11, 63.69, 54.52	61.11	22.20, 21.72, 18.59	20.84	46.53, 42.32, 41.26	43.37
	2						
	3	65.17, 60.17, 63.81	63.05	22.20, 20.52, 21.76	21.49	49.14, 47.97, 45.19	47.43

1) Local water. 2) Gypsum in local water. 3) Gypsum water.

Table 1. Continued

Soil Series	Water Type	Single Ring	$\bar{x}$	Corrected Single Ring	$\bar{x}$	Double Rings	$\bar{x}$
Casa Grande SL	1	4.75, 4.02	4.48	1.92, 1.70	1.81	1.32, 1.04	1.18
	2	4.90, 4.62	4.76	1.93, 1.87	1.90	2.56, 2.32	2.44
	3	4.35, 5.09	4.72	1.76, 2.06	1.89	2.54, 2.32	2.43
Casa Grande	1	0.40, 0.69	0.55	0.16, 0.28	0.22	0.15, 0.37	0.26
	2	1.48, 1.65	1.57	0.60, 0.67	0.64	1.09, 0.69	0.89
	3	0.22, 0.31	0.27	0.09, 0.13	0.11	0.12, 0.22	0.17
Superstition	1	4.36, 3.49	3.93	1.49, 1.19	1.34	1.98, 1.58	1.78
	2	4.55, 3.37	3.96	1.55, 1.15	1.35	2.18, 1.11	1.65
	3	3.77, 4.55	4.16	1.29, 1.55	1.42	1.19, 1.58	1.39
Gadsen	1	0.47, 0.39	0.43	0.20, 0.16	0.18	0.24, 0.24	0.24
	2	1.03, 1.14	1.09	0.43, 0.48	0.46	0.27, 0.63	0.45
	3	0.79, 0.95	0.87	0.33, 0.40	0.37	0.32, 0.37	0.35

1) Local water. 2) Gypsum in local water. 3) Gypsum water.

Table 1. Continued

Soil Series	Water Type	CCHP Amoozemeter	$\bar{x}$	Temp Cell	$\bar{x}$
Gila	1	0.78, 0.49, 1.41	0.89		
	2				
	3	0.34, 1.40, 0.54	0.76	3.06, 2.33	2.70
Pima	1	0.12, 0.08, 0.04	0.08		
	2				
	3	0.01, 0.08, 0.13	0.07	0.06, 0.06	0.06
Vinton	1	3.55, 3.44, 4.93	3.97		
	2				
	3	3.92, 3.58, 3.62	3.71	10.47, 3.82	7.15
Grabe	1	0.48, 0.53, 0.39	0.47		
	2				
	3	0.50, 0.55, 0.72	0.59	1.47, 1.49	1.48
Anthony	1	0.73, 0.59, 0.41	0.58		
	2				
	3	1.01, 0.98, 1.13	1.04	0.94, 0.20	0.57
Brazito	1				
	2				
	3			55.6, 61.2	58.4

1) Local water. 2) Gypsum in local water. 3) Gypsum water.

Table 1. Continued

Soil Series	Water Type	CCHP (Amoozemeter)	$\bar{x}$	Temp Cell	$\bar{x}$
Casa Grande SL	1				
	2				
	3			12.18, 5.78	8.98
Casa Grande SCL	1				
	2				
	3			6.01, 4.40	5.21
Superstition	1				
	2				
	3			3.27, 5.04	4.16
Gadsen	1				
	2				
	3			0.02, 0.02	0.02

1) Local water. 2) Gypsum in local water. 3) Gypsum water.