Pedotransfer Functions for Estimating Saturated Hydraulic Conductivity: Opportunities for Minimizing Uncertainty

Gerard J. Kluitenberg
Kansas State University
Introduction

Saturated Hydraulic Conductivity

“The ease with which pores of a saturated soil transmit water. Formally, the proportionality coefficient that expresses the relationship of the rate of water movement to hydraulic gradient in Darcy’s Law...” (National Soil Survey Handbook, Section 618.50)

Darcy’s Law is

\[ \frac{Q}{At} = K_s (\Delta H/L) \]

where \( \frac{Q}{At} \) is the rate of water flow, \( \Delta H/L \) is the hydraulic gradient, and \( K_s \) is the saturated hydraulic conductivity.
Introduction

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity used by NRCS for numerous interpretations:
- Suitability for irrigation and drainage systems
- Septic tank absorption fields
- Sewage lagoons
- Sanitary landfills
- Irrigation disposal of wastewater

Unfortunately, $K_s$ data are available for relatively few soils because $K_s$ is difficult to measure. Methods are costly, time-consuming, require specialized equipment, and subject to numerous sources of uncertainty.
Introduction

**Estimation of Saturated Hydraulic Conductivity**

Difficulties in obtaining $K_s$ data have motivated effort to estimate $K_s$ from more easily measured soil properties.

Efforts to estimate $K_s$ dates back to at least the 1930s.

Substantial body of work on $K_s$ estimation exists due to efforts of NRCS staff and research contributions from soil science community and related disciplines.

Despite progress, a critical need remains for algorithms that can be used to generate reliable estimates of $K_s$. 
Introduction

**Pedotransfer Functions for Estimation of $K_s$**

The term pedotransfer function (PTF), coined by Bouma (1989), refers to statistical regression equations used to express relationships between soil properties.

In $K_s$ context, PTFs are used to develop relationships between $K_s$ and more easily measured soil properties.

Terminology is new, but concept is old. Many decades-old methods for $K_s$ estimation can be considered PTFs.

Primary benefit of PTF concept?
- Renewed interest in estimation of hydraulic properties
- Focusing of effort in soil science community
Introduction

Pedotransfer Functions for Estimation of $K_s$

Strong interest in PTFs mainly a result of new methods and tools for PTF development:
- Statistical regression techniques
- Artificial neural networks
- Group method of data handling
- Regression tree modeling

Considerable interest in neural network PTF of Schaap et al. (1998) for $K_s$ estimation.

Interest driven, in part, by availability of a graphical user interface (Rosetta) for implementing method.
Outline

• Evaluation of PTFs for Estimating Saturated Hydraulic Conductivity: Results from joint NRCS-KSU research project
• Opportunities for Minimizing Uncertainty
• Questions and Discussion
Evaluation of PTFs for Estimating $K_s$

Project Objective

Evaluate use of Rosetta for benchmark soils by comparing Rosetta $K_s$ estimates with field-measured $K_s$ data.

Methods

Physical property and $K_s$ data measured at sites where NRCS descriptions of soil series had been completed.

The 16 sites (10 benchmark soils) included eight Mollisols, one Alfisol, one Vertisol, two Inceptisols, and one Entisol.
Evaluation of PTFs for Estimating $K_s$

Methods – Soil series used in investigation

<table>
<thead>
<tr>
<th>Soil series</th>
<th>Taxonomic description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mollisols</td>
<td></td>
</tr>
<tr>
<td>Albion*</td>
<td>Coarse-loamy, mixed, superactive, mesic Udic Argiustoll</td>
</tr>
<tr>
<td>Bourbonais</td>
<td>Coarse-silty over sandy or sandy-skeletal, mixed, mesic Fluventic Hapludoll</td>
</tr>
<tr>
<td>Dennis*</td>
<td>Fine, mixed, active, thermic Aquic Argiudoll</td>
</tr>
<tr>
<td>Geary*</td>
<td>Fine-silty, mixed, superactive, mesic Udic Argiustoll</td>
</tr>
<tr>
<td>Harney*</td>
<td>Fine, smectitic, superactive, mesic Pachic Argiustoll</td>
</tr>
<tr>
<td>Irwin*</td>
<td>Fine, mixed, superactive, mesic Pachic Argiustoll</td>
</tr>
<tr>
<td>Morrill</td>
<td>Fine-loamy, mixed, superactive, mesic Typic Argiudoll</td>
</tr>
<tr>
<td>Pawnee*</td>
<td>Fine, smectitic, superactive, mesic Aquic Argiudoll</td>
</tr>
<tr>
<td>Penden*</td>
<td>Fine-loamy, mixed, mesic Typic Calciustoll</td>
</tr>
<tr>
<td>Sibleyville</td>
<td>Fine-loamy, mixed, superactive, mesic Typic Argiudoll</td>
</tr>
<tr>
<td>Ulysses*</td>
<td>Fine-silty, mixed, mesic Aridic Haplustoll</td>
</tr>
</tbody>
</table>
Evaluation of PTFs for Estimating $K_s$

**Methods - Soil series used in investigation**

<table>
<thead>
<tr>
<th>Soil series</th>
<th>Taxonomic description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfisol</td>
<td>Sandy, mixed, mesic, Lamellic Haplustalf</td>
</tr>
<tr>
<td>Pratt*</td>
<td></td>
</tr>
<tr>
<td>Vertisol</td>
<td>Fine, smectitic, superactive, thermic Typic Epiaquert</td>
</tr>
<tr>
<td>Kënoma*</td>
<td></td>
</tr>
<tr>
<td>Inceptisols</td>
<td>Loamy, siliceous, superactive, mesic Lithic Dystrudept</td>
</tr>
<tr>
<td>Basehor</td>
<td>Fine-silty, mixed, superactive, mesic Fluventic Eutrudept</td>
</tr>
<tr>
<td>Bismarckgrove</td>
<td></td>
</tr>
<tr>
<td>Entisols</td>
<td>Coarse-silty, mixed, superactive, nonacid, mesic Typic Udifluvent</td>
</tr>
<tr>
<td>Belvue</td>
<td></td>
</tr>
</tbody>
</table>
Evaluation of PTFs for Estimating $K_s$

Methods

Pit excavated at each site and soil described by NRCS soil scientists.

Samples from each horizon sent to NSSC Soil Survey Laboratory for physical property analysis.
Evaluation of PTFs for Estimating $K_s$

**Methods**

Field measurements of $K_s$ obtained using constant-head well permeameter method (Amoozemeter) with five replicates per horizon.

Where appropriate, horizons less than 15-cm thick were grouped to satisfy constraints of CHWP method.
Evaluation of PTFs for Estimating $K_s$

**Methods**

The 16 sites yielded 53 samples including 14 A horizons, 29 B horizons, and 10 C horizons.

Relatively uniform distribution of textures with the exception of sandy clay.
Evaluation of PTFs for Estimating $K_s$

**Methods**

Estimation of $K_s$ from physical property done using Rosetta (Schaap et al., 2001), and the methods of Ahuja et al. (1989) and Saxton et al. (1986).

Rosetta allows for five hierarchical levels of input data:
- Textural class
- Sand, silt and clay (SSC) percentages
- SSC and bulk density (BD)
- SSC, BD, and 33-kPa water content
- SSC, BD, and 33- and 1500-kPa water contents

Method of Ahuja et al. (1989) uses effective porosity.
Method of Saxton et al. (1986) uses sand and clay percentages and total porosity.
Evaluation of PTFs for Estimating $K_s$

Results – Estimation using Rosetta

Input: Textural Class

Field-Measured $K_s$ (cm/h)

Rosetta-Predicted $K_s$ (cm/h)

$\sum_{i=1}^{n} \left[ \log(K_s) - \log(K'_s) \right]^2$

$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} [\log(K_s) - \log(K'_s)]^2}$

RMSE quantifies deviation from 1:1 line due to both scatter and bias (rotation & translation).
Evaluation of PTFs for Estimating $K_s$

Results – Estimation using Rosetta

- Inputs: Sand, Silt, and Clay Percentages
  - $R^2 = 0.32$
  - $RMSE = 0.756$

- Inputs: SSC and Bulk Density
  - $R^2 = 0.57$
  - $RMSE = 0.651$
Evaluation of PTFs for Estimating $K_s$

Results – Estimation using Rosetta

Inputs: SSC, BD, and 1/3-Bar Water Content

Field-Measured $K_s$ (cm/h)

Rosetta-Predicted $K_s$ (cm/h)

$R^2 = 0.35$
RMSE = 0.769

Inputs: SSC, BD, and 1/3- and 15-Bar Water Contents

Field-Measured $K_s$ (cm/h)

Rosetta-Predicted $K_s$ (cm/h)

$R^2 = 0.32$
RMSE = 0.773
Evaluation of PTFs for Estimating $K_s$

Results - Estimation using Rosetta

Results show only modest correlation between measured and Rosetta-predicted saturated hydraulic conductivity.

Best estimation achieved with combination of sand, silt and clay percentages and bulk density.

The use of 33- and 1500-kPa water contents did not enhance predictive ability over SSC and bulk density.

Rosetta estimates were biased (rotational) towards overestimation at low $K_s$ and underestimation at high $K_s$.

Bias and modest correlation likely a result of the data set used for calibration of Rosetta.
Evaluation of PTFs for Estimating $K_s$

Results – $K_s$ from Ahuja and Saxton Methods

Ahuja Method

\[ R^2 = 0.36 \]
\[ \text{RMSE} = 0.885 \]

Saxton Method

\[ R^2 = 0.64 \]
\[ \text{RMSE} = 0.591 \]
Evaluation of PTFs for Estimating $K_s$

Results – $K_s$ from Ahuja and Saxton Methods

Ahuja Method
- Rotational bias in $K_s$ estimates similar to that for Rosetta.
- Did not perform as well as Rosetta (larger RMSE) due to translational bias.

Saxton Method
- Best of the three PTFs examined (lowest RMSE) due to minimal bias in $K_s$ estimates.
Evaluation of PTFs for Estimating $K_s$

Results - Additional comparisons...

Comparison of Field-Measured $K_s$ and NRCS Field $K_s$ Estimates
Evaluation of PTFs for Estimating $K_s$

Results - Additional comparisons...

Field-measured $K_s$ values fell outside the NRCS assigned range for more than half of the sampled horizons.

Where there was lack of agreement, assigned ranges were generally greater than the field-measured $K_s$ values.

Agreement between field-measured $K_s$ values and assigned range appears to be poorest for Bt horizons.
Evaluation of PTFs for Estimating $K_s$

Conclusions

A high-quality data set has been assembled for evaluating pedotransfer functions for $K_s$ estimation.

The results suggest that Rosetta is not well suited for estimating $K_s$ due to modest correlation with measured values and substantial bias.

Of the PTFs evaluated, the Saxton method proved to be the most effective for estimating $K_s$.

Problems with bias in $K_s$ estimation were most likely a result of the data sets used for PTF calibration.
Opportunities for Minimizing Uncertainty

Database Development

There exists a critical need for a database that contains field-measured $K_s$ data as well as corresponding soil descriptions and physical properties data.

There appears to be widespread agreement in the soil physics community that pedotransfer functions are not working out all that well. Principle problem appears to be lack of data for testing and development.

Most of the existing databases contain little in the way of field-measured $K_s$ data...
Opportunities for Minimizing Uncertainty

Database Development

Perspective needs to be broader than simply developing a database that NRCS can use to evaluate/screen existing pedotransfer functions.

Database is critically needed by the soil science research community to calibrate existing PTFs and guide the development of new tools and methods for estimating $K_s$. 
Opportunities for Minimizing Uncertainty

PTF Development

We can expect significant advances in the tools and methods for developing pedotransfer functions.

Advances in tools and methods will likely improve our ability to incorporate the expert knowledge of field soil scientists (e.g., identification of “overriding conditions” in Section 618.50 of Handbook).

Soil science research community needs the expertise of NRCS soil scientists to keep this process focused and moving in the right direction.
Opportunities for Minimizing Uncertainty

$K_s$ Measurement

Improved methods for measuring $K_s$ are needed...
Opportunities for Minimizing Uncertainty

Summary

• Databases for evaluating and developing PTFs
• Advances in tools and method for PTF development
• Advances in method for $K_s$ measurement
Questions & Discussion