View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Sydney eScholarship

Efficient methods for predicting soil hydraulic properties

Budiman Minasny

BScAgr – Universitas Sumatera Utara
MAgr in Soil Science – The University of Sydney

A thesis submitted
in fulfillment of the requirements
for the degree of
Doctor of Philosophy

Department of Agricultural Chemistry and Soil Science
The University of Sydney
New South Wales
Australia

MM

Certificate of originality

I hereby certify that the text of this thesis contains no material which has been accepted as part of the requirements for any degree or diploma in any university nor any material previously published or written unless the reference to this material is made.

Budiman Minasny

Abstract

Both empirical and process-simulation models are useful for evaluating the effects of management practices on environmental quality and crop yield. The use of these models is limited, however, because they need many soil property values as input. The first step towards modelling is the collection of input data. Soil properties can be highly variable spatially and temporally, and measuring them is time-consuming and expensive. Efficient methods, which consider the uncertainty and cost of measurements, for estimating soil hydraulic properties form the main thrust of this study.

Hydraulic properties are affected by other soil physical, and chemical properties, therefore it is possible to develop empirical relations to predict them. This idea quantified is called a pedotransfer function. Such functions may be global or restricted to a country or region. The different classification of particle-size fractions used in Australia compared with other countries presents a problem for the immediate adoption of exotic pedotransfer functions. A database of Australian soil hydraulic properties has been compiled. Pedotransfer functions for estimating water-retention and saturated hydraulic conductivity from particle size and bulk density for Australian soil are presented. Different approaches for deriving hydraulic transfer functions have been presented and compared. Published pedotransfer functions were also evaluated, generally they provide a satisfactory estimation of water retention and saturated hydraulic conductivity depending on the spatial scale and accuracy of prediction. Several pedotransfer functions were developed in this study to predict water retention and hydraulic conductivity. The pedotransfer functions developed here may predict adequately in large areas but for site-specific applications local calibration is needed.

There is much uncertainty in the input data, and consequently the transfer functions can produce varied outputs. Uncertainty analysis is therefore needed. A general approach to quantifying uncertainty is to use Monte Carlo methods. By sampling repeatedly from the assumed probability distributions of the input variables and evaluating the response of the model the statistical distribution of the outputs can be estimated. A modified Latin hypercube method is presented for sampling joint multivariate probability distributions. This method is applied to quantify the uncertainties in pedotransfer functions of soil hydraulic properties. Hydraulic properties predicted using pedotransfer functions

developed in this study are also used in a field soil-water model to analyze the uncertainties in the prediction of dynamic soil-water regimes.

The use of the disc permeameter in the field conventionally requires the placement of a layer of sand in order to provide good contact between the soil surface and disc supply membrane. The effect of sand on water infiltration into the soil and on the estimate of sorptivity was investigated. A numerical study and a field experiment on heavy clay were conducted. Placement of sand significantly increased the cumulative infiltration but showed small differences in the infiltration rate. Estimation of sorptivity based on the Philip's two term algebraic model using different methods was also examined. The field experiment revealed that the error in infiltration measurement was proportional to the cumulative infiltration curve. Infiltration without placement of sand was considerably smaller because of the poor contact between the disc and soil surface.

An inverse method for predicting soil hydraulic parameters from disc permeameter data has been developed. A numerical study showed that the inverse method is quite robust in identifying the hydraulic parameters. However application to field data showed that the estimated water retention curve is generally smaller than the one obtained in laboratory measurements. Nevertheless the estimated near-saturated hydraulic conductivity matched the analytical solution quite well. Th author believes that the inverse method can give a reasonable estimate of soil hydraulic parameters. Some experimental and theoretical problems were identified and discussed.

A formal analysis was carried out to evaluate the efficiency of the different methods in predicting water retention and hydraulic conductivity. The analysis identified the contribution of individual source of measurement errors to the overall uncertainty. For single measurements, the inverse disc-permeameter analysis is economically more efficient than using pedotransfer functions or measuring hydraulic properties in the laboratory. However, given the large amount of spatial variation of soil hydraulic properties it is perhaps not surprising that lots of cheap and imprecise measurements, e.g. by hand texturing, are more efficient than a few expensive precise ones.

Acknowledgements

I'd like to thank Prof. Alex. McBratney for his supervision and advice, his suggestions and constructive criticism greatly improved the quality of this work. I'd like to express my gratitude to my parents and family for their trust and support throughout the years and to whom this work is dedicated.

I'd like to thank Dr. Keith L. Bristow, CSIRO Land and Water Townsville, Dr. Hamish P. Cresswell, CSIRO Land and Water Canberra, for providing the Australian hydraulic data set. I am grateful to all soil scientists who have made the soil physical measurements and provided their data for public-domain use, which became the main source of information for this thesis. I also thank Dr. Art. Warrick, University of Arizona, and Dr. Jirka Simunek, US Salinity Laboratory, for providing the computer code for soil-water simulations, and Dr. Rutger Vervoort for introducing me to the SWAP program. I appreciate all those who had provided source code for public-domain use, which made life easier and programming less painful.

Thanks to Mr. Damien Field, Mr. Mohan Teeluck and Mr. Brendan George and all others who had provided helpful discussion and criticism which improved the readability and quality of the writing.

I acknowledge the Faculty of Agriculture for providing the F.H. Loxton scholarship. Thanks are due to all the staff in Department of Agricultural Chemistry and Soil Science at the University of Sydney for their assistance. The Australian Centre for Precision Agriculture provided some work for me during the years (thanks Brett). Thanks to all my friends in the department, especially Herr Stephen Wagner for sharing his foods, and stories. My gratitude to all the students of Advanced Soil Physics classes in 1998, 1999 and 2000, for helping with the measurements in Narrabri.

Table of contents

Chapter II. The Disc Permeameter

Chapter III. Inverse methods predicting soil hydraulic properties

PART B. New Research

Chapter IV. Development and evaluation of hydraulic pedotransfer functions for Australian soil

Chapter VI. Estimation of sorptivity from disc permeameter measurements

Chapter VII. Inverse method for predicting soil hydraulic properties from disc permeameter data

Chapter VIII. Discussion: – The efficiency of various approaches to obtaining estimates of soil hydraulic properties

List of Figures

Chapter V

Chapter VIII

List of Tables

Chapter V

Chapter VI

List of symbols and abbreviations

Greek symbols

Symbol	Description	Dimension	Applied unit
α	scaling parameter of van Genuchten equation	L^{-1}	m^{-1}
α_g	sorptive number, Gardner's scaling parameter	L^{-1}	m^{-1}
α	probability level	-	-
β	parameter vector	variable	
β	Box-Cox transformation parameter	-	-
δ	parameter correction vector (Levenberg-Marquardt procedure)	-	-
Δ	small change or difference		
ε	error	variable	
ϕ	porosity	$L^3 L^{-3}$	$m^3 m^{-3}$
ϕ_e	effective porosity	$L^3 L^{-3}$	$m^3 m^{-3}$
ϕ_0	matrix flux potential	$L^2 T^{-1}$	$m^2 s^{-1}$
γ	proportionality constant (Haverkamp's equation),	-	-
γ	dimensionless parameter (Barry *et al*'s equation),	-	-
γ	semivariance	variable	
η	step-size for correction vector (Levenberg-Marquardt procedure)	-	-
η_w	viscocity of water	$M L^{-1} T^{-1}$	Pa s
φ	angle between correction & gradient vector (Levenberg-Marquardt procedure)	-	-
κ	shape factor (Haverkamp's equation)	-	-
λ	exponent in Brooks-Corey equation,	-	-
λ	eigenvalue	-	-
λ	Levenberg-Marquardt damping factor	-	-
λ_c	macroscopic capillary length	L	mm
λ_m	microscopic mean pore size	L	mm
μ	mean	variable	
ν	empirical lateral wetting front coefficient, related to disc size	L^{-1}	mm
θ	volumetric water content	$L^3 L^{-3}$	$m^3 m^{-3}$
θ_r	residual water content	$L^3 L^{-3}$	$m^3 m^{-3}$
θ_s	saturated water content	$L^3 L^{-3}$	$m^3 m^{-3}$
θ_0	water content at applied potential h_0	$L^3 L^{-3}$	$m^3 m^{-3}$
θ_n	initial water content	$L^3 L^{-3}$	$m^3 m^{-3}$
θ_{-10}	water content at -10 kPa	$L^3 L^{-3}$	$m^3 m^{-3}$
θ_{-33}	water content at -33 kPa	$L^3 L^{-3}$	$m^3 m^{-3}$
θ_{-1500}	water content at -1500 kPa	$L^3 L^{-3}$	$m^3 m^{-3}$
ρ_b	bulk density	$M L^{-3}$	$Mg\ m^{-3}$

ρ_s	particle density	$M\ L^{-3}$	$Mg\ m^{-3}$
ρ_w	density of water	$M\ L^{-3}$	$Mg\ m^{-3}$
σ	standard deviation	variable	
σ_w	surface tension of water	MT^{-2}	Pa
σ_g	geometric standard deviation of mean particle-size diameter	L	mm
τ	pore tortuosity factor,	-	-
υ	dimensionless scaling parameter for lateral wetting front	-	-

Roman alphabet

Symbol	Description	Dimension	Applied unit
a	dimensionless length (Wooding's equation)	-	-
A	Philip's parameter relating to steady-state infiltration rate (one-dimensional infiltration)	$L\ T^{-1}$	$m\ s^{-1}$
A'	Philip's parameter relating to steady-state infiltration rate (two-dimensional infiltration)	$L\ T^{-1}$	$m\ s^{-1}$
b	Campbell's water retention fractal coefficient,	-	-
b	constant relating shape factor for the soil-water diffusivity function = 0.55	-	-
B	coefficient in Kozeny-Carman equation	$L\ T^{-1}$	$mm\ h^{-1}$
c	empirical coefficient		
C	differential water capacity	L^{-1}	m^{-1}
C_o	organic carbon content (% by weight)	$L\ L^{-1}$	$dag\ kg^{-1}$
CP	cumulative amount of particle-size	$M\ M^{-1}$	-
d_g	geometric mean of particle size diameter	L	mm
dI/dt	derivation of cumulative infiltration with respect to time (infiltration rate)	$L\ T^{-1}$	$m\ s^{-1}$
D	soil water diffusivity,	$L^2\ T^{-1}$	$m^2\ s^{-1}$
D	fractal dimension of particle size distribution	-	-
D_1	fractal dimension by Tyler & Wheatcraft (1989)	-	-
D_2	fractal dimension by Chang & Uehara	-	-
D_3	fractal dimension by Kravchenko & Zhang	-	-
E	mathematical expectation	-	-
$\mathbf{e}$	eigenvector	-	-
f	grain size distribution index (Bloemen's PTF)	-	-
f	a function of	-	-
$\mathbf{g}$	gradient vector	-	-
F	transfer function	-	-
F^{-1}	inverse function	-	-
h	pressure head of soil moisture	L	m
h_0	applied pressure head	L	mm
h_n	initial soil pressure head	L	m
h_{surf}	depth of water ponded at soil surface	L	mm
h_{str}	minimum soil water pressure at which there is a continuous gas phase	L	mm
H	hydraulic head of soil moisture	L	m
$\mathbf{H}$	Hessian matrix	-	-
i	infiltration rate	$L\ T^{-1}$	$m\ s^{-1}$
$\mathbf{I}$	identity matrix	-	-
I	cumulative infiltration	L	m
I_s	amount of water needed to wet up a layer of contact sand	L	mm
$\mathbf{J}$	Jacobian matrix	-	-
K	hydraulic conductivity	$L\ T^{-1}$	$m\ s^{-1}$
K_s	saturated hydraulic conductivity	$L\ T^{-1}$	$m\ s^{-1}$

K_0	hydraulic conductivity at supply potentail h_0	L T^{-1}	m s^{-1}
K_n	initial soil hydraulic conductivity	L T^{-1}	m s^{-1}
l	tortuosity factor in van Genuchten equation	-	-
L	logarithm of maximum likelihood	variable	
L_s	thickness of a layer of contact sand	L	mm
L	lower triangular matrix	-	-
m	exponent in the Kozeny-Carman equation	-	-
m	the exponent parameter in the van Genuchten equation m = 1-1/n	-	-
m	number of equiprobable sections in the sectioning method	-	-
N	number of data	-	-
NZ	number of water retention curves	-	-
n	curve shape parameter in van Genuchten equation	-	-
nf	number of fractions in particle size distribution	-	-
ns	number of samples	-	-
np	number of parameters	-	-
O	objective function	variable	
pF	$\log_{10}$ (-h/cm)	-	-
p_{samp}	percentage of distribution correctly sampled from the prescribed intervals	-	-
P	principal component	variable	
$P_{<2}$	mass of particles < 2μm	M M^{-1}	dag kg^{-1}
P_{2-20}	mass of particles 2 – 20 μm	M M^{-1}	dag kg^{-1}
P_{2-50}	mass of particles 2 – 50 μm	M M^{-1}	dag kg^{-1}
$P_{20-2000}$	mass of particles 20 – 2000 μm	M M^{-1}	dag kg^{-1}
$P_{50-2000}$	mass of particles 50 – 2000 μm	M M^{-1}	dag kg^{-1}
PS	particle size limit	L	μm
Q	cumulative water outflow	L^3	m^3
	specific water-yield	L	mm
Q_∞	steady state cumulative water outflow	L^3	m^3
Q^*	dimensionless flux (Wooding's equation)	-	-
q	steady-state infiltration rate	L T^{-1}	m s^{-1}
q	flow response	variable	
$\hat{q}$	predicted flow response	variable	
q^*	dimensionless steady-state rate (Wooding's equation)	-	-
q_∞	steady-state infiltration rate	L T^{-1}	m s^{-1}
R	correlation coefficient	-	-
R^2	coefficient of determination	-	-
r	residual vector	variable	
R_s	soil mechanical resistance	M L^{-1} T^{-2}	MPa
r	radial coordinate	L	m
r	particle size radius	L	μm
r^*	dimensionless disk radius (Wooding's equation)	-	-
r_0	disk radius	L	mm
r_1	lateral wetting front	L	mm
$\mathrm{r_n}$	normally distributed random numbers	-	-
$\mathrm{r_u}$	uniformly distributed random numbers	-	-

S	sensitivity coefficient	variable	
S_0	sorptivity	L $T^{-1/2}$	mm $s^{-1/2}$
S_e	effective saturation, or normalized water content	-	-
t	time	T	s
t_c	time when capillary absorption dominates	T	s
t_s	time needed to wet-up a layer of contact sand	T	s
t_{exp}	experimental time limit for the disc permeameter to wet up certain depth	T	s
t_{geom}	time after which geometric effect of the disc dominates over the capillary sorption	T	s
t_{grav}	time needed to reach steady-state in infiltration	T	s
t_α	Student's t at probability level α	-	-
u	fuzzy membership	-	-
u_c	fuzzy membership at class c	-	-
v	weight set for different data set	-	-
$\mathbf{V}$	variance-covariance matrix	-	-
w	weighting factor for individual data	-	-
W	weighting factor	-	-
W_L	water storage to a depth L	L	m
x	input or independent variables	variable	
X	sample variables	variable	
y	output or dependent variables	variable	
$\hat{y}$	predicted output	variable	
z	vertical coordinate	L	m
z_1	wetting front on the vertical axis	L	mm
Z	number of data points on a water retention curve	-	-

Abbreviations

Abbreviation	Description
AIC	Akaike Information Criterion
ANP	parametric PTF using neural networks
AWC	available water content
CEC	cation exchange capacity
Corr	correlation
Cov	covariance
GMER	geometric mean error ratio
GSDER	geometric standard deviation of error ratio
GRMSR	geometric root mean squared residuals
LHS	Latin hypercube sampling
MAE	mean absolute error
MD	mean deviations (for water retention curve)
ME	mean error
MLH	modified latin hypercube sampling
MSM	modified sectioning method
MLR	multiple linear regression
MLP	multilayer perceptron
MRP	parametric PTF using multiple linear regression
PSD	particle-size distribution
PTF	pedotransfer function
PWP	permanent wilting point
QCV	cross-validation prediction error
RMSE	root mean squared error
RMSR	root mean squared of residuals
RMSD	root mean squared deviations (for water retention curve)
RR	relative residuals
SE	standard error
SRS	simple random sampling
SMD	soil moisture deficit
SSE	sum of squared error
SSR	sum of squared residuals
Var	variance
WS	water storage

Part of this thesis have been submitted and/or published in scientific journals:

Chapter IV –

Minasny, B., McBratney, A.B., Bristow, K.L., 1999. Comparison of different approaches to the development of pedotransfer functions for water retention curves. *Geoderma* 93, 225-253.

Minasny, B., and McBratney, A.B., 2000. Hydraulic conductivity pedotransfer functions for Australian soil. *Australian Journal of Soil Research* 38, 905-926.

Minasny, B., McBratney, A.B., 2001. The Australian soil texture boomerang: a comparison of the Australian and USDA/FAO soil particle-size classification systems. *Australian Journal of Soil Research* 39, 1443-1451.

Chapter V –

Minasny, B., McBratney, A.B., 2002. Uncertainty analysis for pedotransfer functions. *European Journal of Soil Science* 53, 417-430.

Chapter VI –

Minasny, B., McBratney, A.B., 2000. Estimation of sorptivity from disc-permeameter measurements. *Geoderma* 95, 305-324.

Chapter VIII –

Minasny, B., and McBratney, A. B. (2002). The efficiency of various approaches to obtaining estimates of soil hydraulic properties. *Geoderma* 107, 55-70.