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Agricultural Systems, Vol. 52, No. 2/3, pp. 331 353, 1996
Published by Elsevier Science Ltd
Printed in Great Britain
0308-521X/96 $15.00 + .00

PII: S0308-521X(96)00001-7

Indirect Estimation of Soil Hydraulic Properties to Predict Soybean Yield Using GLYCIM

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(Received 16 May 1995; revised version received 27 November 1995; accepted 29 November 1995)

ABSTRACT

*GLYCIM, a mechanistic model of soybean (*Glycine Max *L.) growth and development, requires soil hydraulic parameters as input. These data are usually not readily available. The objective of this study was to compare yields calculated with measured hydraulic properties to those calculated with hydraulic properties estimated from soil texture and bulk density. We reviewed estimation methods and chose two methods to estimate a soil moisture release function and two methods to obtain saturated hydraulic conductivity. Both methods use soil texture and bulk density as predictors. Soil water retention predicted by these methods correlated well with measured soil water retention whereas the estimation of saturated hydraulic conductivity was poor. Soybean yields were simulated using GLYCIM with and without irrigation for seven locations in Mississippi, USA, using seven years of weather records. Simulated yields were affected more by the method of estimating the moisture release curve than by the method of estimating saturated hydraulic conductivity. The average simulated yields from estimated properties were higher than those from measured properties because estimated water retention provided more available water. Correlation between yields simulated using measured and estimated hydraulic properties was higher under non-irrigated conditions than with irrigation. Averaging yields over years with different weather conditions greatly improved the correlations. Published by Elsevier Science Ltd*

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INTRODUCTION

GLYCIM is a detailed process level model of soybean (*Glycine Max* L.) development and yield (Acock & Trent, 1991). Presently, it is being tested on several farms in the Mississippi delta, where it is used to forecast management effects on soybean yield (Reddy *et al.*, 1995). Water availability and uptake are functions of the soil hydraulic properties used as input in the model. These hydraulic properties include the soil water retention function (water content as a function of soil matric potential) and saturated hydraulic conductivity (K_{sat}). Data to construct these relationships have been measured on soil samples collected at the farms where GLYCIM is being tested. As the use of GLYCIM is expanded to other regions it may not always be feasible to collect detailed data on soil hydraulic properties. Measurement of soil hydraulic properties is not a routine procedure, and requires trained personnel and special equipment.

A number of methods to estimate soil hydraulic properties from simple data have been proposed and verified for both regional and national data sets (Rawls *et al.*, 1991). These methods use soil texture, bulk density, and some measure of pore size distribution. The use of soil hydraulic properties estimated from simple and easily available data would allow GLYCIM to be used in locations where soil hydraulic properties have not been measured but where data such as soil texture and bulk density are available.

The best index to determine the fitness of a particular estimation method in a simulation model is the targeted output for the model. The selection of the targeted output varies with the model used. Wösten *et al.* (1990) used water storage when comparing four methods to estimate hydraulic conductivity. Anderson *et al.* (1987) used predicted water stress when comparing different methods of averaging hydraulic properties. An appropriate indicator of fit in a crop model would be the correlation between yields predicted using measured and estimated soil hydraulic properties. This value represents the integrated effects of variables and input data used in the model.

The objective of this work was to assess the use of estimated hydraulic properties in place of measured properties in GLYCIM. The hydraulic properties to be estimated are the soil water retention function and saturated hydraulic conductivity. Predicted soybean yield is the targetted output used to assess the fitness of the estimation methods used.

OVERVIEW OF METHODS TO ESTIMATE SOIL HYDRAULIC PROPERTIES FROM READILY AVAILABLE DATA

The subject of indirect estimation of soil hydraulic properties from readily available data has been addressed by many authors. Here we present a brief review in this paper to justify our approach and to provide the reader with general guidelines on literature in this area.

Published reports on methods to calculate soil hydraulic parameters from simpler data are summarized in Tables 1–4. The tables cover about 30% of materials published on this topic and represents the majority of current approaches. To save space, we will reference the papers using the numbering of Table 1.

Soil data used for the estimation of hydraulic properties usually include soil texture, organic matter content, soil bulk density, and/or soil porosity. Clay mineral composition can be important if montmorillonite, iron oxides, or vermiculite are present in the clay fraction [25]. It was suggested that cation exchange capacity can be used to express the influence of mineral composition [36]. Indices based on field observations of soil structure have been used successfully [11, 25, 37]. Soil aggregate distribution has also been used successfully [30, 49], but has not become widespread because aggregate distribution is not readily available. Several methods that use a quantification of soil structure have also been proposed [42, 43].

The most commonly used predictor of soil hydraulic properties is soil texture, especially in the dry range of water contents. Percentages of sand, silt and clay available from soil survey data have been used extensively (Table 1). The estimates of soil hydraulic properties have often been improved by using subfractions like coarse sand, fine sand, coarse silt, etc. [32, 39, 41, 42]. Others have recommended the use of particle size distribution parameters such as median diameter, variance of particle size, or indices showing the skewness of the distribution function [8, 19, 45]. Recently a fractal theory relating the number of particles to their size has been employed to calculate a parameter that relates particle size distribution and water retention [29].

The most commonly available soil properties are soil texture and bulk density. Values for these properties can be found in almost all soil survey publications. Methods that use these properties have also been most widely tested and used. Therefore, we will evaluate methods that use soil texture and bulk density to estimate soil hydraulic properties for GLYCIM.

Soil water retention functions

There are three common methods to estimate the soil water retention function, each with several variations. The first method estimates water contents for a selected set of soil matric potentials. For each matric potential, a separate regression equation relates water content to soil data such as texture, bulk density or organic matter [2, 4, 14, 18, 22, 26, 31, 35–37, 39, 41]. The second method estimates the coefficients in equations that define water content as a function of soil matric potential, or vice versa. One common equation often used to describe the soil water retention function is a power law function. Examples are the Brooks–Corey equation:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{\psi_b}{\psi}\right)^{\lambda} \tag{1}$$

Campbell's equation:

$$\theta = \theta_s\left(\frac{\psi_b}{\psi}\right)^{\lambda} \tag{2}$$

and Gardner's equation:

$$\theta = A\psi^{-B} \tag{3}$$

Another often used water retention equation is the logistic type equation. Examples are van Genuchten's equation (van Genuchten, 1980):

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (\alpha\psi)^n]^m} \tag{4}$$

and Brutsaert's (Brutsaert, 1966) equation:

$$\frac{\theta}{\theta_s} = \frac{1}{1 + (\alpha\psi)^n} \tag{5}$$

In eqns (1)–(5), θ is the volumetric water content, ψ is the soil matric potential, θ_s is the volumetric water content at saturation, ψ_b is the matric potential when air starts to enter the soil (air entry matric potential or 'bubbling pressure'), and θ_r is the residual water content. Depending on which equation is used, one or more of the coefficients, λ, ψ_b, A, B, θ_r, α, n, and m have to be estimated from readily available data.The third method to estimate water retention begins with equations for moisture retention for each textural component: sand, silt and clay. The moisture content of the soil at a particular matric potential is calculated as a weighted average of the moisture contents predicted by these equations based on the relative amounts of sand, silt and clay [16, 28, 46, 47]. Because this does not give good results it is not commonly used.

The precision of the water retention estimates using these methods differs widely and reported correlation coefficients between measured and estimated values vary from 0·99 to 0·5. The accuracy of estimates can usually be improved when soil samples are grouped into homogeneous sets. Textural class, taxonomic class, genetic horizons, or position in the soil profile have been proved to be good indicators for grouping [14–16, 27, 31, 32, 37, 47]. Several authors have suggested that the coefficients in eqns (1)–(3) can be made constant within textural classes [1, 10, 17, 20]. Alternatively, a group number can be directly incorporated into the regression equations [43, 44].

The use of one or two pairs of measured water content and matric potential levels has been shown to enhance the predictive capabilities of indirect estimation techniques. Water contents corresponding to matric potentials of −33 or −1500 kPa were found suitable [4, 12, 22, 26, 40]. Soil matric potential at the air entry pressure has also been used [18, 29].

Saturated hydraulic conductivity

Estimation of saturated hydraulic conductivity (K_{sat}) from readily available soil data is generally less successful than estimation of water retention. The high variability of K_{sat} and its dependence on soil macrostructure introduces large uncertainties into the estimations. Scale effects, i.e. differences between measurement scales of K_{sat} and the soil data used as predictors, are much more important for K_{sat} than for water retention [13]. Nevertheless, similar soil properties are used to estimate K_{sat} as are used for water retention functions.

Two methods to estimate K_{sat} have provided reasonable results. One uses a polynomial regression of $\log(K_{sat})$ on percentages of soil texture components and porosity [2, 23]. Another method is based on Kozeny–Karman capillary flow theory, and employs equations that, in general, look like:

$$K_{sat} = B\phi_e^N \tag{6}$$

where B and N are parameters to be indirectly estimated, ϕ_e is effective porosity which is taken as the difference between total porosity, and either residual volumetric water content [9, 33] or volumetric water content corresponding to 33 kPa matric potential [13, 48]. Regression equations for indirect estimations of soil hydraulic properties are mostly viewed as having regional importance [21]. Large errors in some cases (Bork & Diekrügger, 1990) and good accuracy in others (de Jong, 1982) were observed when the equations developed for one region were used in another.

TABLE 1
Summary of Published Work on Estimation of Soil Hydraulic Properties

No.	*WR*[a]	*SHC*[b]	*SV*[c]	*EQ*[d]	*RV*[e]	*Grouping*[f]	*Data used*[g]	*Reference*
1	+	+	–	PL	–	TC	C,S	McCuen *et al.*, 1981
2	+	+	+	PL	–	–	C,S,O,ρ	Rawls *et al.*, 1992
3	+	+	–	PL	–	–	C,S,ϕ	Rawls & Brakensiek, 1989
4	+	–	+	–	FC,WP	–	C,S,O,ρ	Rawls & Brakensiek, 1989
5	+	–	–	PL	–	–	C,ρ,Si	McBride & Mackintosh, 1984
6	+	+	–	PL	–	–	C,S,ϕ	Saxton *et al.*, 1986
7	+	–	–	VG	–	–	C,Si,O,ρ	Wösten *et al.*, 1990
8	+	–	–	PL	–	–	T7,O	Bloemen, 1980
9	–	+	–	PL	h_s	TC		El-Kadi, 1985*a*
10	+	–	–	PL,VG,BR	-	TC	C,S	El-Kadi, 1985*b*
11	+	+	–	–	–	Mrp	C,S,ρ	McKeague *et al.*, 1984
12	+	–	–	PL	FC,WP	–	C,S,ρ,O	Ahuja *et al.*, 1985
13	–	+	–	–	FC	TC	C,ϕ	Messing, 1989
14	+	–	+	–	–	TC	C,ρ	Petersen *et al.*, 1968
15	+	–	–	VG	–	TC,Hz	C,Si,O,ρ,T7	Wösten & van Genuchten, 1988
16	+	–	–	CO	Matric potent			Schuh *et al.*, 1987
17	+	–	–	PL	–	TC	TC	Clapp & Hornberger, 1978
18	+	–	+	–	AE,h_s,WP	–	–	Rogowsky, 1971
19	+	+	–	PL,VG	–	–	T7,ρ	Mishra *et al.*, 1989
20	+	–	–	PL	–	TC	–	de Jong, 1982
21	+	–	–	PL	–	D	C,S	Oosterveld & Chang, 1980
22	+	–	+	–	FC,WP	–	C,S,ρ	Williams *et al.*, 1992*b*
23	–	+	–	GA	–	–	S,ρ	Jaynes & Tyler, 1984
24	+	–	–	PL	–	–	S,Si,C,ρ	Ghosh, 1980
25	+	–	–	PL	–	Mrp,MC,TC	C,Si,S	Williams *et al.*, 1983
26	+	–	+	–	AE,FC,WP	–	–	de Jong, 1983
27	+	–	–	BA	–	Hz	C,S,ρ	Varallyay *et al.*, 1982
28	+	–	–	CO	–	–	T7,ρ	Arya & Dierolf, 1992
29	+	+	–	PL	AE	–	C,S,Si	Chang & Uehara, 1992

30	+	–	–	BA	–	–	ϕ,ASD	Wu & Vomocil, 1992
31	+	–	+	–	–	Hz	C,S,ρ	Varallyay *et al.*, 1982
32	+	–	–	BA	–	Hz	C,S,ρ	Pachepsky *et al.*, 1992
33	+	+	–	PL	–	–	T7,ϕ	Mishra & Parker, 1992
34	+	+	–	PL	–	–	S,C,ρ	Campbell & Shiozava, 1992
35	+	+	+	PL,VG	–	–	S,C,O,ρ	Rawls *et al.*, 1992
36	+	–	+	–	–	D	S,C,O,ρ,CEC	Baumer, 1992
37	+	–	+	–	–	Hz	S,C,Si,ρ,O	Thomassen & Carter, 1992
38	+	–	–	CO	–	–	T7,ASD,ρ	Gupta & Ewing, 1992
39	+	–	+	–	–	–	ρ,ϕ,S,FS,C	Dane & Puckett, 1992
40	+	–	–	PL	FC,WP	–	C,S,ρ	Williams & Ahuja, 1992
41	+	–	+	–	–	TC	C,S,Si,FS,ρ,ESP	Rajkai & Varallyay, 1992
42	+	–	–	PL	–	–	C,FS,O,CS	Williams *et al.*, 1992*b*
43	+	–	–	PL	–	–	C,ρ,STR	Williams *et al.*, 1992*b*
44	+	–	–	PL	–	–	C,ρ,STR,TeX	Williams *et al.*, 1992*b*
45	+	–	–	VG	–	–	T7,ϕ	Jonasson, 1992
46	+	–	–	CO	–	–	CS,O	Ambroise *et al.*, 1992
47	+	–	–	CO	–	TC	C,S,Si	Schuh, 1992
48	–	+	–	PL	FC	–	Si	Naney *et al.*, 1992
49	+	–	+	–	–	–	T7,ASD	Zeiliguer, 1992

[a] Water retention estimations: + yes, – no.
[b] Saturated hydraulic conductivity estimations: + yes, – no.
[c] Water contents estimated separately for preselected matric potentials: + yes, – no.
[d] Estimating coefficients in water retention equations: PL, power law equations (1)–(3); VG, van Genuchten's equation (4); BA, Brutsaert's equation (5); CO, composing soil water retention from water retentions of soil components.
[e] Reference water retention to improve estimations: AE, air entry matric potential; FC, water content at 33 kPa; WP, water content at 1500 kPa.
[f] Grouping that improved estimations: TC, textural class; Mrp, field morphological structure; MC, clay mineral composition; Hz, genetic horizons; D, depth in the profile.
[g] Data used in the indirect estimations: C, clay content; S, sand content; Si, silt content; ρ, soil bulk density; ϕ, porosity; CS, coarse sand; FS, fine sand; PSZ, particle size distribution; ASD, aggregate size distribution; STR, index of field structure (1, massive soil; 2, soil with pedality; TeX, textural group index; O, organic matter content.

MATERIALS AND METHODS

Measured hydraulic properties

The farms where the soils were sampled are located in Sunflower, Lee, Bolivar, and Coahoma counties in the Mississippi delta area of Mississippi.

A pressure plate apparatus was used to determine the moisture release characteristics. The pressures used were, 1, 10, 33, 67, 100, 500, and 1500 kPa. Measurements were repeated on five replicate cores 76 mm in diameter and 10 mm high. The hydrometer method was used to determine soil texture. Saturated soil hydraulic conductivities were determined in the lab on soil cores 76 mm in diameter and 76 mm high using the constant head and/or falling head method. The reported value is the geometric mean of five measurements. The sampling locations, soil classifications and textural data are in Table 2.

The water retention function in GLYCIM is represented by Marani's equation (Acock & Trent, 1991):

$$\theta = \theta_r + \left(\frac{\psi}{\psi_{\text{sat}}}\right)^{\frac{1}{\eta}} \times (\theta_s - \theta_r) \tag{7}$$

where θ_s and ψ_s are moisture content and matric potential near saturation, and θ_r is a residual water content. θ_s is the water content at 1·0 kPa matric potential. θ_r, ψ_{sat} and η are parameters that are fit using a non-linear least squares optimization method. Eqn (7) is similar to eqn (1) except that ψ_{sat} is used in place of ψ_b. Hydraulic conductivity at any water content is calculated as:

$$\mathrm{K}(\psi) = \mathrm{K}_{\text{sat}} \left(\frac{\psi_{\text{sat}}}{\psi}\right)^{\frac{1}{\eta}+2} \tag{8}$$

Hydraulic properties in GLYCIM

GLYCIM uses a hybrid of capacity-based and diffusivity models to simulate infiltration and redistribution of water. The soil profile is considered to be two-dimensional and is represented by grid cells in the vertical and horizontal (across row) directions. During infiltration, a capacity type model is used to fill the soil with water. The upper level of water capacity is the water content at −33 kPa matric potential. When the water content of a cell exceeds this value the excess is moved to the next

TABLE 2
Classification, Textures, and Bulk Densities of Soils Used in the Study

Soil	*Depth (cm)*	*Sand*	*Silt (kg/kg)*	*Clay*	ρ_b *(Mg/m³)*
Forestdale clay loam, Sunflower Co.,	0–23	21·6	46·7	31·7	1·12
fine, montmorillonitic, non-acid, thermic	23–31	25·3	31·0	43·0	1·24
Vertic Haplaquepts	31	42·1	26·0	31·9	1·01
Ora loam, Lee Co., fine-loamy, siliceous,	0–20	41·9	47·3	10·7	1·42
thermic, Typic Fragiudults	20–32	43·0	43·0	14·0	1·49
	32–48	32·8	50·0	17·2	1·34
	48 +	50·8	34·6	14·6	1·28
Sharkey Silty clay loam, Sunflower Co., very fine, montomorillonitic, non-acid, thermic Vertic Haplaquepts	0–16	14·9	45·8	39·3	1·09
	17–27	6·3	40·0	53·7	1·18
	28 +	4·8	37·9	57·3	1·11
Dubbs sandy loam, Bolivar Co., fine-	0–14	46·4	43·7	9·9	1·16
silty, mixed, thermic Typic Hapludalfs	15 +	38·9	48·0	13·1	1·35
Dundee sandy loam, Bolivar Co., fine-	0–14	54·8	34·5	10·7	1·17
silty, mixed, thermic Aeric Ochraqualfs	15–37	31·7	45·8	22·5	1·32
	38 +	56·6	29·4	14·0	1·25
Sharkey silty clay loam, Coahoma Co.,	0–20	16·7	43·6	39·7	1·07
very fine, montomorillonitic, non-acid, thermic Vertic Haplaquepts	20 +	15·9	40·6	43·5	1·17
Sharkey silty clay, Bolivar Co., very fine,	0–33	2·9	52·7	44·4	1·08
montmorillonitic, non-acid, thermic	33–49	14·8	56·0	29·1	1·16
Vertic Haplaquepts	49 +	11·2	47·1	41·6	1·11

cell below. Excess water drains from the profile after the last cell is filled. This method assumes infiltration is instantaneous. Redistribution of water in both lateral and vertical directions is carried out by a diffusivity model. The hydraulic diffusivity at a particular water content is calculated from the slope of the water retention function and hydraulic conductivity at that water content. Water transport is driven by gradients in moisture content. All the water is assumed to infiltrate, runoff is not accounted for.

Estimation of soil hydraulic properties in GLYCIM

We selected two methods to estimate water retention functions and two methods to estimate K_{sat}. The methods to estimate soil water retention functions are from Rawls *et al.* (1992) and Williams *et al.* (1992*a*) The method of Rawls uses soil texture to calculate parameters for the Brooks–Corey equation (eqn (1), θ_r, λ and ψ_b). The method of Williams uses soil texture to calculate the coefficients of an equation that expresses a power law (eqn (2)). The equations used to obtain these parameters from soil texture and bulk density are in Table 3.

Saturated hydraulic conductivity was estimated using equations suggested by Dane & Puckett (1992) and Rawls *et al.* (1992). In the method of

TABLE 3
Equations Used to Calculate the Soil Water Retention Function

Williams *et al.*, 1992*a*

$$A = 1{\cdot}839 + 0{\cdot}257 * \log(\mathrm{CLAY}^{a}) + 0{\cdot}381 * 2{\cdot} - 0{\cdot}0001 * \mathrm{SAND} * \mathrm{SAND}$$

$$B = -0{\cdot}303 + 0{\cdot}093 * \log(\mathrm{BD}) + 0{\cdot}0565 * \log(\mathrm{CLAY}) - 0{\cdot}00003 * \mathrm{SAND}$$

$$\theta = \exp(A + B \times \log(\psi^{b}))/100.$$

Rawls *et al.*, 1992

$$\begin{aligned}\lambda = {} & \exp(0{\cdot}7842831 + 0{\cdot}0177544{\cdot}\mathrm{SAND} \\ & -1{\cdot}062498{\cdot}\phi - 0{\cdot}00005304{\cdot}\mathrm{SAND}^2 \\ & -0{\cdot}00273493{\cdot}\mathrm{CLAY}^2 + 1{\cdot}11134946{\cdot}\phi^2 - 0{\cdot}03088295{\cdot}\mathrm{SAND}{\cdot}\phi \\ & +0{\cdot}00026587{\cdot}\mathrm{SAND}^2{\cdot}\phi^2 - 0{\cdot}00610522{\cdot}\mathrm{CLAY}^2{\cdot}\phi^2 \\ & -0{\cdot}00000235{\cdot}\mathrm{SAND}^2{\cdot}\mathrm{CLAY} + 0{\cdot}00798746{\cdot}\mathrm{CLAY}^2{\cdot}\phi \\ & -0{\cdot}00674491{\cdot}\phi^2{\cdot}\mathrm{CLAY}\ )\end{aligned}$$

$$\begin{aligned}\psi_s = {} & -\exp(5{\cdot}3396738 + 0{\cdot}1845038{\cdot}\mathrm{CLAY} \\ & -2{\cdot}48394546{\cdot}\phi - 0{\cdot}00213853{\cdot}\mathrm{CLAY}^2 - 0{\cdot}04356349 \\ & -\mathrm{SAND}{\cdot}\phi - 0{\cdot}61745089{\cdot}\mathrm{CLAY}{\cdot}\phi + 0{\cdot}00143598{\cdot}\mathrm{SAND}^2{\cdot}\phi_2 \\ & -0{\cdot}00001282{\cdot}\mathrm{SAND}^2{\cdot}\mathrm{CLAY} + 0{\cdot}00895359{\cdot}\mathrm{CLAY}^2{\cdot}\phi \\ & -0{\cdot}00072472{\cdot}\mathrm{SAND}^2{\cdot}\phi + 0{\cdot}0000054{\cdot}\mathrm{CLAY}^2 \\ & -\mathrm{SAND} + 0{\cdot}50028060{\cdot}\phi^2{\cdot}\mathrm{CLAY})\end{aligned}$$

$$\begin{aligned}\theta_r = {} & -0{\cdot}0182482 + 0{\cdot}00087269{\cdot}\mathrm{SAND} + 0{\cdot}00513488{\cdot}\mathrm{CLAY} + 0{\cdot}02939286{\cdot}\phi \\ & -0{\cdot}00015395{\cdot}\mathrm{CLAY}^2 - 0{\cdot}0010827{\cdot}\mathrm{SAND}{\cdot}\phi - 0{\cdot}00018233 \\ & -\mathrm{CLAY}^2{\cdot}\phi^2 + 0{\cdot}00030703{\cdot}\mathrm{CLAY}^2{\cdot}\phi - 0{\cdot}0023584{\cdot}\phi^2{\cdot}\mathrm{CLAY}\end{aligned}$$

[a] Fraction of textural component expressed as percentage.
[b] ψ (bars).

Dane and Puckett, K_{sat} is a function of clay content. Rawls' method uses bulk density, sand and clay content. The coefficients for these equations are in Table 4.

Predicted water contents at selected matric potentials were obtained from the Brooks–Corey (eqn (1)) and power law (eqn (2)) equations. The coefficients were obtained from the equations in Table 3 using soil texture and bulk density as predictors. Marani's equation (eqn (7)) was fit to water content-matric potential data estimated by the two methods and the resultant parameters were used in GLYCIM. We used seven years of daily weather data from Starkville, Mississippi. The data included daily radiation, windrun, rainfall, and maximum and minimum air temperatures. The conditions represented by the weather data ranged from very dry to very wet. We ran the model for irrigated and non-irrigated conditions. For the irrigated conditions GLYCIM was programmed automatically to add enough water to fill the soil profile to 60% of its capacity when a threshold level of moisture stress was reached. The threshold level of moisture stress was defined as two consecutive days of stress lasting a period of five or more hours each day. The combinations of estimation methods for the water retention function and hydraulic conductivity used in the simulations are listed in Table 5.

RESULTS

Estimated vs. measured water contents for the methods of Rawls and Williams are given in Fig. 1. Whereas the method of Williams produced a

TABLE 4

Equations Used to Calculate Hydraulic Conductivity (K_{sat}) from Soil Texture and Bulk Density

Dane & Puckett, 1992

$$K_{sat}{}^{a} = 4{\cdot}36E{-}05*\exp(-0{\cdot}1975*CLAY^{b})$$

Rawls *et al.*, 1992

$$\begin{aligned} K_{sat} = {} & 24{\cdot}*\exp(19{\cdot}52348 * \phi^{c} - 8{\cdot}96847 - 0{\cdot}028212*CLAY \\ & + 0{\cdot}00018107 \times S2 - 0{\cdot}0094125 \times CLAY^2 - 8{\cdot}395215 \times \phi^2 \\ & + 0{\cdot}077718 \times SAND \times \phi \\ & - 0{\cdot}00298 \times SAND^2 \times \phi^2 \\ & - 0{\cdot}019492 \times CLAY^2 \times \phi^2 \\ & + 0{\cdot}0000173 \times SAND^2 \times CLAY \\ & + 0{\cdot}02733 \times CLAY^2 \times \phi \\ & + 0{\cdot}001434 \times SAND^2 \times \phi \\ & - 0{\cdot}0000035 \times CLAY^2 \times SAND^{b}) \end{aligned}$$

[a] m/s.
[b] Clay or sand expressed as a percentage.
[c] $\phi = 0{\cdot}9 \times (1-\rho_b/2{\cdot}65)$.

TABLE 5
Summary Statistics for Regressions of Measured vs. Predicted Variables

Source	*Method*[a]		*n*	*Intercept*	*Standard deviation*	*Coefficient*	*Standard deviation*	*Standard error*	R^2 (%)
	WRC	K_{sat}							
Water content						m^3/m^3			
	W		120	0·039	0·014	0·859	0·046	0·044	76·1
	R			−0·053	0·017	1·102	0·057	0·054	74·1
K_{sat}						cm/d			
		DP	20	−0·10	0·274	0·945	0·391	1·87	49·5
		R		0·76	0·171	0·300	0·243	0·73	27·9
Yield non-irrigated						kg/ha			
	W	DP	49	1005	205·9	0·83	4·856	804·17	73·7
	R	DP		994·3	204·8	0·90	4·83	799·82	76·8
	R	R		981·4	211·8	0·91	4·996	827·35	76·3
Irrigated	W	DP	49	2327·4	317·9	0·41	6·212	961·82	29·4
	R	DP		2056·2	277·8	0·49	5·429	840·58	44·3
	R	R		2131·3	275·2	0·48	5·377	832·56	43·0
WHC						m^3/m^3			
	W		120	0·07	0·017	0·759	0·223	0·016	39·2
	R			0·213	0·02	−1·019	0·271	0·019	44·1

[a] The methods for the water retention curve and K_{sat} are:
1. W, Williams *et al.*, 1992*a*;
2. R, Rawls *et al.*, 1992;
3. DP, Dane & Puckett, 1992.

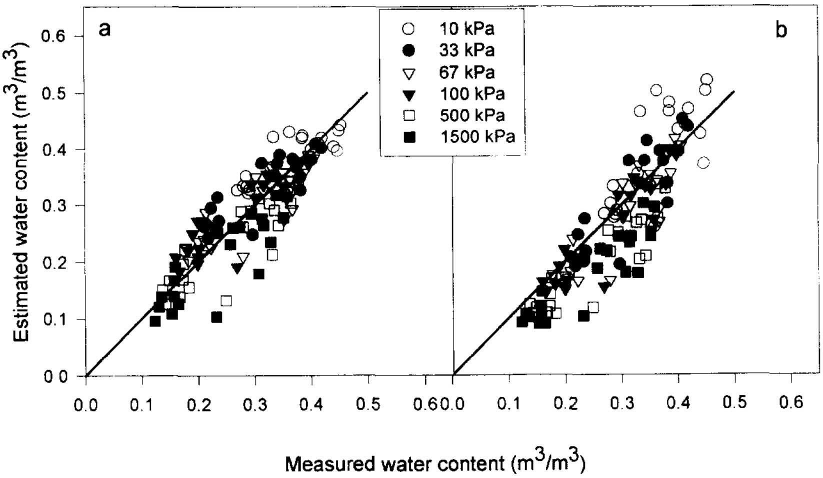

Fig. 1. Measured vs. estimated water contents from two estimation methods: (a) Williams *et al.* (1992*a*); (b) Rawls *et al.* (1992).

slightly concave dependence of estimated water contents on measured values (Fig. 1a), the method of Rawls displayed a slightly convex dependence (Fig. 1b). The standard error for the method of Williams was smaller (Table 5). Both methods tended to underestimate low water contents and overestimate high water contents (Fig. 1). However, the method of Rawls overestimated water contents in the wet range to a greater extent (Fig. 1b).

The estimated saturated hydraulic conductivities were poorly correlated with the measured values (Fig. 2 and Table 5). The standard error was smaller for the method of Rawls (Table 5). This illustrates the difficulty of estimating saturated hydraulic conductivity from simpler data such as soil texture and porosity. Saturated hydraulic conductivity is highly variable and is strongly affected by soil conditions such as compaction, and the presence of macropores and plant roots. It is also strongly scale dependent, i.e. the measured value can change by large amounts when the size of the measured area changes.

Simulations without irrigation

The yields predicted with estimated (Y_e) and measured (Y_m) soil properties for non-irrigated conditions are given in Fig. 3 and Table 5. The two estimation methods do not give greatly differing results. Large differences between Y_e and Y_m could be found for some soils in a particular year. The regression lines showed that the values of Y_e were generally larger than values of Y_m. Model runs using the same method to predict the moisture release curve (Rawls) but different methods to predict saturated hydraulic

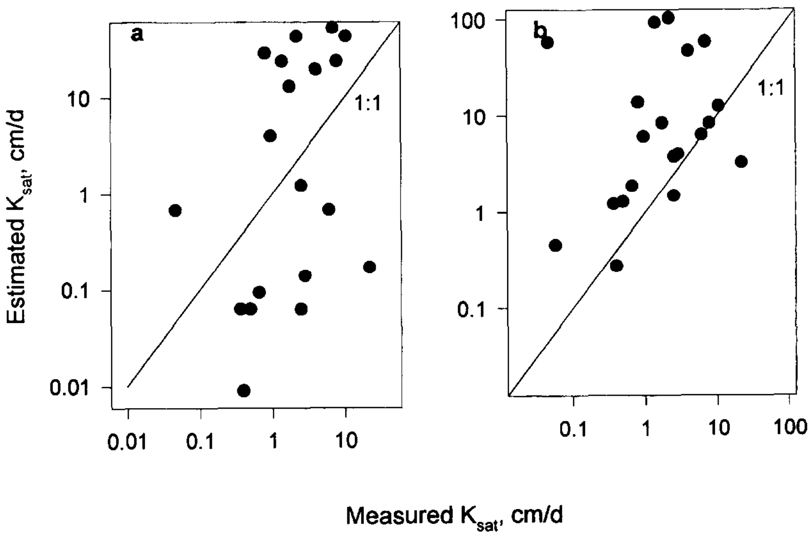

Fig. 2. Measured vs. estimated saturated hydraulic conductivity (K_{sat}) from two estimation methods: (a) Dane & Puckett (1992); (b) Rawls *et al.* (1992).

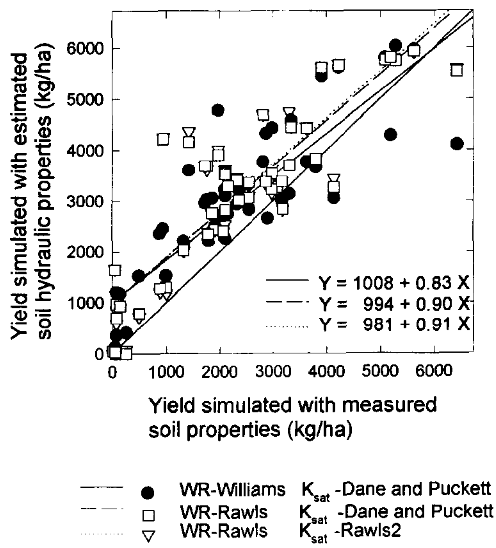

Fig. 3. Yields of non-irrigated soybean using measured and estimated soil hydraulic properties for seven soils and seven weather patterns.

conductivity (Dane–Puckett and Rawls) gave nearly identical results (Fig. 3 and Table 5).

When yields were averaged for each soil over the seven years of weather data the correspondence between Y_m and Y_e was improved (Fig. 4a). The

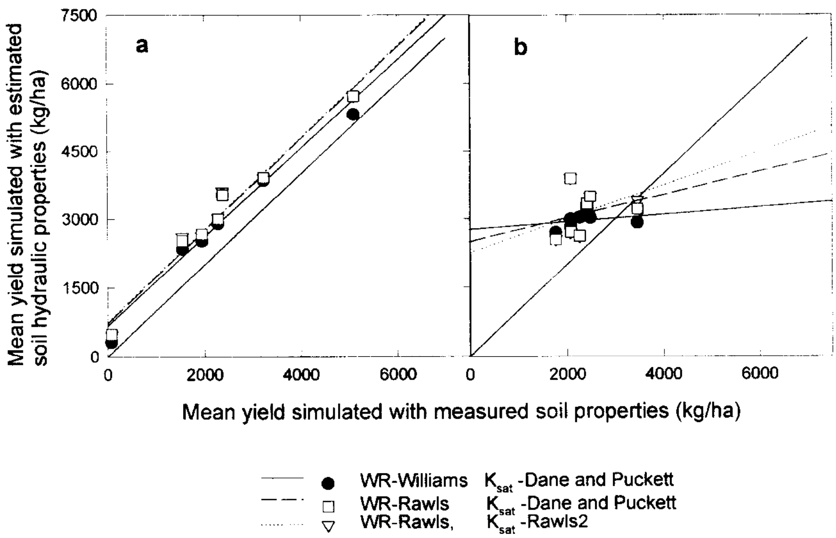

Fig. 4. Averaged yields simulated with measured and estimated soil hydraulic properties and with no irrigation (a) averaged for each soil over different weather patterns; (b) averaged for each year of weather data over all soils.

method of Williams, which gave smaller errors in water retention estimations, provided better correspondence between Y_m and Y_e. There was a poor correlation between Y_m and Y_e when the yields were pooled by year, i.e. each data point is a mean of the seven soils for one year of weather data (Fig. 4b).

Simulations with irrigation

The correlation between Y_m and Y_e was much lower for the irrigated simulations than for the non-irrigated ones (Fig. 5 and Table 5), although the standard error of the regression was similar. The use of estimated hydraulic properties resulted in overestimation at small yields and underestimation at large yields. When yields were averaged for each soil over the seven years of weather data, the correspondence between Y_m and Y_e became better (Fig. 6a), although the tendency to overestimate low yields persisted. Averaging of yields over all soils, as in non-irrigated crops, did result in an increase in correlation between Y_m and Y_e (Fig. 6b).

DISCUSSION

The measured and predicted water contents were well distributed around a 1:1 line (Fig. 1) but the simulated yields using estimated hydraulic

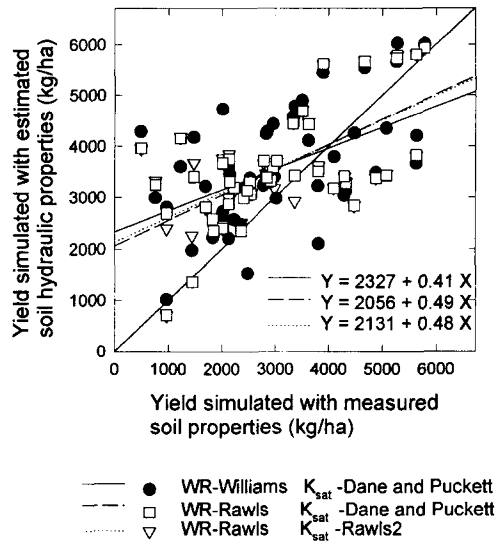

Fig. 5. Yields of irrigated soybean simulated using measured and estimated soil hydraulic properties for seven soils and seven weather patterns.

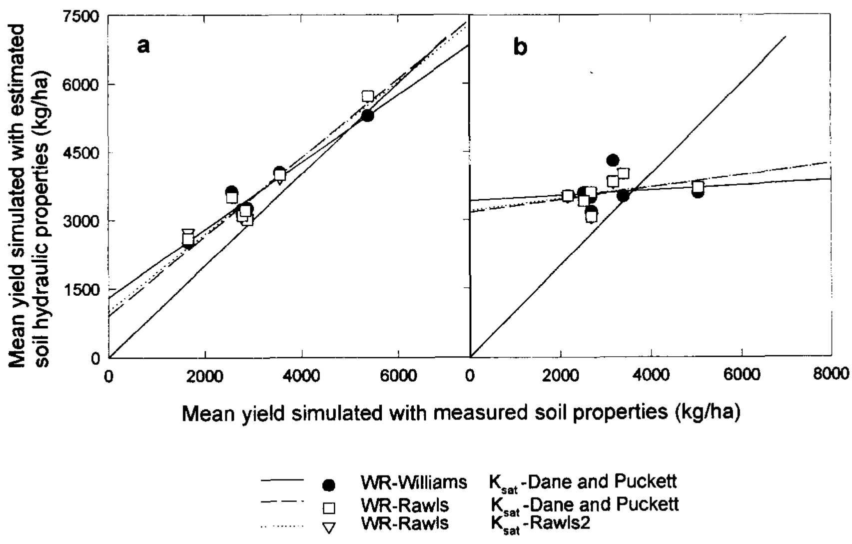

Fig. 6. Averaged yields simulated with measured and estimated soil hydraulic properties and with irrigation: (a) averaged for each soil over different weather patterns; (b) averaged for each year of weather data over all soils.

properties were consistently larger than yields calculated using measured properties. This is because GLYCIM is a capacity-based model and an important parameter is the difference between the water contents at 33 and

1500 kPa, the water holding capacity. The estimation methods we used generally overpredicted this value (Fig. 7). Nagarajan *et al.* (1993) also noted underprediction of yield by the model SOYGRO, which uses similar water transport simulation code, due to poor estimation of available water holding capacity. The method of Williams estimated water holding capacity and better than that of Rawls (Fig. 7 and Table 5). As a result the yield predictions using data estimated using the method of Williams had a lower standard error. The regression slope for water holding capacity by the method of Rawls was close to −1. This is because the method overestimates water content at 10 and 33 kPa and underestimates water content at 1500 kPa. Good estimates of water content at these points would greatly improve the use of estimated soil properties.

Yields calculated using different methods to estimate K_{sat} and the same method to estimate water retention were not different (Figs 3–5). This suggests that GLYCIM is not sensitive to the value of saturated hydraulic conductivity. This is because K_{sat} is not used in infiltration calculations. Furthermore, the shape of the hydraulic conductivity vs. matric potential relationship is determined by the shape of the water retention function (eqn (8)), K_{sat} only scales the function. Hydraulic conductivity is used to calculate diffusivity but the magnitude of the value drops off rapidly from saturation. The root growth submodel of GLYCIM allows roots to grow actively in the soil regions where water is more available. Therefore, water content patterns are affected more by water uptake by roots than by capillary redistribution. This minimizes the importance of soil hydraulic conductivity in water uptake.

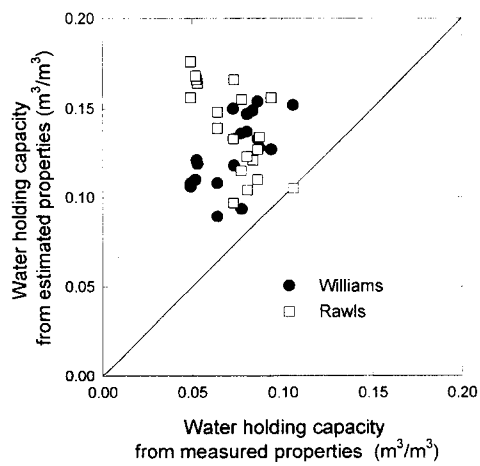

Fig. 7. Measured water holding capacity and water holding capacity from estimated water contents.

Averaging simulated yields over several years with different weather conditions resulted in a strong dependence of Y_e on Y_m. The reason for this is probably that the average for each soil represents simulations over a wide range of water contents. The combinations of dry and wet conditions smooth the effects of different values of the hydraulic parameters. Anderson *et al.* (1987) also reported that in spite of large differences in infiltration parameters there were only small differences in the 30-year average stress day index. The averaging underscores the importance of the water holding capacity as an integrative parameter of soil water retention. The averaging also reflects the correlations for estimated and measured water contents over a wide range of values as shown in Fig. 1.

Averaging yields calculated using estimated and measured hydraulic properties over all soils does not provide close correspondence of yields for a particular year (Figs 4b and 6b). Yields calculated with estimated properties vary less than yields calculated with measured properties. This is related to overestimation of water holding capacity, because larger water holding capacity values diminish the influence of water stresses on yields.

For non-irrigated crops, the largest differences were encountered for the Coahoma County Sharkey and Dundee soils (Table 2), and for irrigated crops the largest differences were found for the Forestdale soil and Dundee. The Dundee soil is a light sandy soil of mixed mineralogical composition, whereas the Coahoma Sharkey soil is a silty clay loam and the Forestdale soil is clay. Both the Sharkey and Forestdale soils have significant montmorillonite contents. This suggests that swelling soils may require different equations to estimate water retention.

The differences between Y_e and Y_m were larger with irrigation when compared to no irrigation. This is because the errors due to using estimated hydraulic properties tend to accumulate each time the soil is filled with water. The timing of stress and the water application also vary depending on the hydraulic parameters used. Low yields were overestimated, probably because soils with higher water holding capacity required larger amounts of irrigation water and the intervals between periods of stress were shorter.

The results of this paper indicate that the use of estimated hydraulic properties may result in unreasonable errors if the validation studies or predictions for a particular year are the objectives. This is in accordance with the results of Anderson *et al.* (1987) who concluded that use of averaged soil property data results in relatively large errors for individual year predictions. However, long-term predictions of management effects on yields may well be possible with estimated hydraulic properties. If the model, for example, is used to forecast the need for irrigation, the use of estimated soil properties may be possible. In the range of yield above 3400 kg/ha where irrigation was applied the correspondence between Y_m and Y_e was good (Fig. 5). It is in this yield range that irrigation was most efficient.

CONCLUSIONS

We evaluated the effect of estimated soil hydraulic properties in place of measured properties on simulated yields calculated by GLYCIM. We used published equations that were developed from large databases to estimate soil hydraulic properties from soil texture and bulk density for several soils in the Mississippi delta region. We found that crop yields calculated with estimated hydraulic properties could differ significantly from the yields calculated with measured hydraulic properties for a particular year and soil. Yields calculated with estimated properties were consistently larger than those calculated with measured properties which we attribute to overestimation of the water holding capacity. Long-term yield projections based on averaging yields over several years with different weather scenarios correlated well for estimated and measured hydraulic properties when both non-irrigated and irrigated crops were simulated.

The accuracy of the indirect methods for water content estimation was relatively low. The equations in Tables 3 and 4 were obtained from regression using large regional databases. Locally derived equations to estimate soil hydraulic properties from readily available soil data can be more accurate than equations derived from large regional databases (Wösten *et al.*, 1990; Wösten & van Genuchten, 1988). It may be worthwhile to collect the data needed to build a local database and develop regression equations.

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