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Accuracy of the Saxton-Rawls Method for Estimating the Soil Water Characteristics for Mineral Soils of Malaysia

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ABSTRACT

The purpose of this study was to determine the accuracy of the Saxton-Rawls method in estimating the soil water characteristics of a wide range of mineral soils of Malaysia. This study found that it was necessary to calibrate the Saxton-Rawls method for the soils of Malaysia. The developed equation for calibration was $\hat{P}_i = a \cdot P_i(1 - P_i)$, where P_i and $\hat{P}_i$ are the uncalibrated and calibrated estimated values, respectively, for the soil sample no. *i*, and the parameter values of *a* were 2.225, 1.605, and 1.528 (for saturation, field capacity, and permanent wilting point) respectively. The calibrated method was validated against three independent soil data sets. The validation tests showed that the calibrated method remained stable and was more accurate than that without any calibration, by an average between 8 to 49%.

Keywords: Organic matter, Saxton-Rawls, soil water characteristics, soil water retention, texture

INTRODUCTION

Soil water characteristic describes the relationship between the soil matric potential and soil volumetric or gravimetric water content (Jury and Horton, 2004). It is a vital soil physical property because it describes how strongly a soil holds onto water. It also reveals the maximum amount of water could be stored by soil (i.e., water content at saturation point) and the maximum amount of water potentially available to plants (i.e., the difference in the water content between the field capacity point and permanent wilting point).

The measurement of soil water characteristics, however, is both time-consuming and expensive (Janik *et al*., 2007). Consequently, many methods or equations exist to estimate the soil water characteristics from multiple soil properties, typically soil texture, bulk density, and organic matter, as described in Saxton and Rawls (2006). Gijsman *et al*. (2002) compared the accuracy of eight modern estimation methods against the field data across many regions in USA. They concluded that the texture-based method by Saxton *et al*. (1986) was the most accurate. The Root Mean Square Error (RMSE) for the method proposed by Saxton *et al*. (1986), for example, was lower by 64% as compared to the average RMSE for the other methods used. One main advantage of the method by Saxton *et al*. (1986) is that it requires only information on the soil texture (sand and clay fractions) and organic matter (in per cent) to predict the characteristics of soil water. Recently, Saxton and Rawls (2006) improved the method by calibrating it against over 1700 different soil

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types stored in the USDA/NRCS National Soil Characterization database (Soil Survey Staff, 2004).

Consequently, the objective of this study was to determine the accuracy of the Saxton-Rawls method to estimate the soil water characteristics of mineral soils of Malaysia. The soil water characteristics of interest in this study were the estimation of the volumetric soil water content at saturation, field capacity, and permanent wilting point.

MATERIALS AND METHODS

The equations used to estimate the characteristics of soil water are listed in Saxton and Rawls (2006), whereby the equation for the soil water content at permanent wilting point is:

$$PWP = \theta_{1500t} + (0.14\theta_{1500t} - 0.02) \qquad [1]$$

with

$$\theta_{1500t} = -0.024S + 0.487C + 0.006OM + 0.005(S \times OM) - 0.013(C \times OM) + 0.068(S \times C) + 0.031 \qquad [2]$$

where PWP is the soil water content at permanent wilting point (m^3 m^{-3}), S and C are the sand and clay contents, respectively (fraction), and OM is the organic matter content (%). For the soil water content at field capacity, the equation is:

$$FC = \theta_{33t} + (1.283\theta_{33t}^2 - 0.374\theta_{33t} - 0.015) \qquad [3]$$

with

$$\theta_{33t} = -0.251S + 0.195C + 0.011OM + 0.006(S \times OM) - 0.027(C \times OM) + 0.452(S \times C) + 0.299 \qquad [4]$$

where FC is the soil water content at the field capacity (m^3 m^{-3}). Finally, the equation used to estimate the water content of soil at saturation is:

$$SAT = \theta_{33} + \theta_{(S-33)} - 0.097S + 0.043 \qquad [5]$$

with

$$\theta_{(S-33)} = \theta_{(S-33)t} + 0.636\theta_{(S-33)t} - 0.107 \qquad [6]$$

and

$$\theta_{(S-33)t} = 0.278S + 0.034C + 0.022OM - 0.018(S \times OM) - 0.027(C \times OM) - 0.584(S \times C) + 0.078 \qquad [7]$$

where SAT is the soil water content at saturation (m^3 m^{-3}).

Four soil data sets, obtained from the literature, were compiled for this study. These data sets comprised only the mineral soils of Malaysia, with a wide range of particle size distribution. The first data set was used to determine the accuracy of the Saxton-Rawls method for the mineral soils of Malaysia. This data set was also used to calibrate the Saxton-Rawls method to improve its estimation accuracy. In order to validate the accuracy and stability of the calibrated Saxton-Rawls method, three more independent data sets were used.

The first data set was from Maene *et al.* (1983), who did extensive compilation and measurement on several physical properties of Malaysian soils, comprised 503 samples from 113 soil types from 61 soil series that cover six soil orders, namely Entisols, Inceptisols, Spodosols, Alfisols, Ultisols, and Oxisols. The measurements for each soil include texture, pH, organic carbon, bulk density, and soil water characteristics. These properties were typically measured for several consecutive soil layers from the surface down to 1.0 m depth. For some soils, however, these properties were measured to depths reaching 2.5 m and below. It is important to note that not all soil samples in the register were used in this study. The samples discarded include the ones with missing required data or, in rare cases, those with unusually high volumetric water content (≥1.0 m^3 m^{-3}). This reduced the total number of soil samples selected to only 270. Meanwhile, the sand content for these final samples ranged from 1.5 to 94.0% (standard deviation = 23.7%), whereas the clay content ranged from 2.2 to 89.6% (standard deviation = 20.9%), and the organic matter content that ranged from 0.0 (trace) to 5.3% (standard deviation = 0.7%).

The second data set comprised 192 soil samples from Maesschalck *et al*. (1983). These soil samples were collected from 16 experimental plots, covering approximately 0.12 ha of the Puchong farm at Universiti Pertanian Malaysia (now known as Universiti Putra Malaysia). In each plot, the soil samples were collected at every successive 0.1 m soil layer from the soil surface to 1.2 m depth. Although these samples were collected from an area classified as Bungor soil series (Typic Paleudult), the textures of these samples differed widely from sandy loam to clay. The content of sand ranged from 35.8 to 66.9% (standard deviation = 7.1%), the clay content ranged from 16.1 to 43.5% (standard deviation = 5.9%), and the organic matter content that ranged from 0.9 to 3.3% (standard deviation = 0.6%).

The third data set, taken from Teh (1996), comprised nine soil types with a wide range of textural classes collected from 0-150 mm of soil depth. The nine soil series were Munchong (Typic Hapluodox), Melaka (Xanthic Hapludox), Rengam (Typic Paleudult), Bungor (Typic Paleudult), Serdang (Typic Paleudult), Holyrood (Typic Kandiudult), and Sg. Buloh (Spodic Quartzipsamment). These soil series were collected from various locations in UPM campus, as well as from Sg. Buloh (for Holyrood and Sg. Buloh soil series). The sand content of the nine soil series ranged from 18.0 to 87.1% (standard deviation = 26.3%), the clay content that ranged from 10.0 to 72.7% (standard deviation = 20.8%), and the organic matter content that ranged from 0.9 to 3.2% (standard deviation = 0.8%).

The fourth data set, taken from Hamdan *et al*. (1999), comprised 12 A-horizons (typically the first 100 mm soil depth) and 12 B-horizons (typically from 100 to 450 mm soil depth). The soils were from 12 soil series, namely Bukit Termiang (Typic Hapludult), Musang (Typic Paleudult), Ulu Dong (Typic Paleudult), Durian (Plinthaquic Paleudult), Kerait (Aquic Paleudult), Nyalau (Typic Dystrochrept), Bekenu (Typic Paleudult), Tarat (Typic Hapludox), and the last four soil series were Rengam, Munchong, Serdang, and Bungor (their soil taxonomic classifications are as before). These soils were sampled from various locations in Peninsular Malaysia (seven soils) and West Sarawak (five soils) in Malaysia. One soil sample, however, was discarded (Tarat series, B-horizon sample) due to its unusually high volumetric water content (≥ 1.0 m^3 m^{-3}). The sand content of the 23 samples ranged from 5 to 75% (standard deviation = 24.3%), the clay content that ranged from 17 to 74% (standard deviation = 16.4%), and the organic matter content which ranged from 0.2 to 4.6% (standard deviation = 1.0%).

For all the four data sets, determination of the soil water characteristics was done using the pressure plate method (Richards, 1947). Meanwhile, the determination of organic carbon was carried out using the Walkley-Black dichromate titration method (Walkley and Black, 1934), with organic matter content taken as 1.72 × organic carbon.

An error index, Mean Absolute Error (MAE), was used to determine the mean error of estimation by the Saxton-Rawls method. Thus, MAE (in percentage) was calculated as:

$$MAE\ (\%) = \frac{100}{N} \cdot \sum_{i=1}^{N} \frac{\left| O_i - P_i \right|}{O_i} \qquad [8]$$

where i is the sample number (i = 1 to N), N is the total number of sample; and O_i and P_i are the observed (measured) and predicted (estimated) values, respectively, for sample i. A large MAE denotes a large mean error in the estimates.

The data analysis was done using Microsoft Excel 2003 (Microsoft Inc., Washington), whereas the calibration of the Saxton-Rawls method was done using Excel's Solver add-in, which uses a non-linear optimization algorithm known as Generalized Reduced Gradient (Lasdon *et al*., 1978).

RESULTS AND DISCUSSION

The mean estimation error (represented by the MAE index) by the Saxton-Rawls method ranged from 17.6 to 21.3% (with a mean of 19.2%) for the first data set (*Fig. 1*). Although the Saxton-

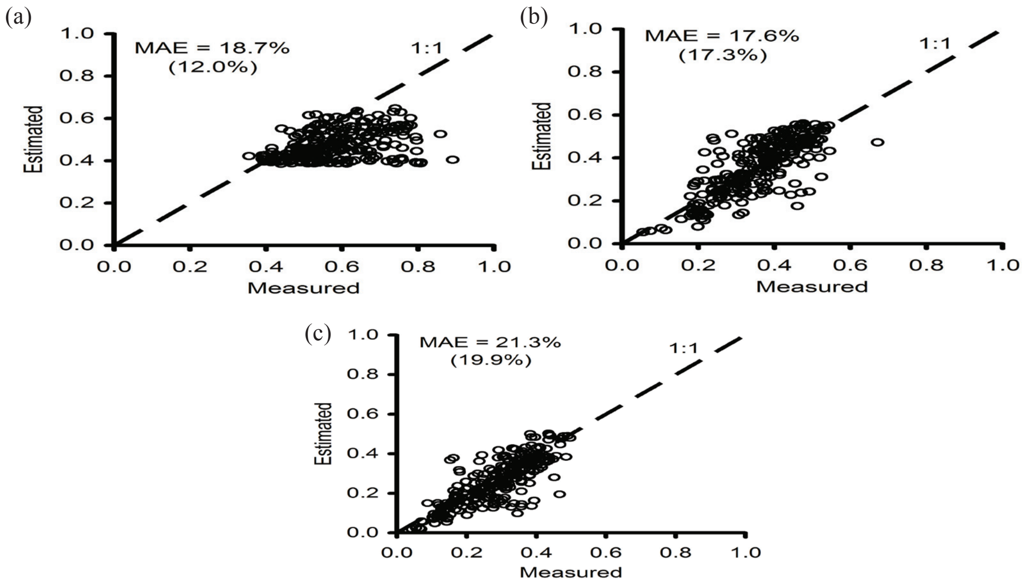

Fig.1: Estimation accuracy by the Saxton-Rawls method (uncalibrated) for the first data set from Maene et al., (1983). The plots are for volumetric soil water content at: a) saturation, (b) field capacity, and (c) permanent wilting point. Values in brackets are the standard deviation for the estimation error index, MAE (Mean Absolute Error), and the dashed diagonal line is the line of agreement

Rawls method tended to underestimate the soil water content at saturation (*Fig. 1a*), it showed none to little bias in the estimation of soil water content at field capacity and permanent wilting point (*Figs. 1b* and *1c*).

In an attempt to increase estimation accuracy, the following quadratic equation was used to calibrate the estimates to agree more closely with the measured values:

$$\hat{P}_i = a \cdot P_i(1 - P_i) \quad [9]$$

where P_i and $\hat{P}_i$ are the uncalibrated and calibrated estimated values, respectively, for soil sample *i*, and *a* is a parameter where its value is such that the mean difference between the estimated and measured values are minimized. In other words, the value for *a* is determined in such a way that the MAE is minimized. The Solver tool included in Microsoft Excel was used to determine the respective *a* values for estimating the soil water content at saturation, field capacity, and permanent wilting point (Table 1). Meanwhile, the calibration of the Saxton-Rawls method using Eq. [9] (with appropriate *a* values from Table 1) reduced the mean MAE to 16% in the first data set, i.e., a reduction by 17% as compared to the uncalibrated Saxton-Rawls method (Table 2). After the calibration, MAE was found ranged from 14.4 to 18.1% as compared to 17.6 to 21.3% for the uncalibrated method.

TABLE 1
The value of the parameter *a* in Eq. [2] for calibrating the Saxton-Rawls method to estimate the volumetric soil water content at saturation, field capacity, and permanent wilting point

Soil water characteristics	*a*
Saturation	2.225
Field capacity	1.605
Permanent wilting point	1.528

Eq. [9] and the best-fitted *a* values (Table 1) were used again, unchanged, in the estimation of the soil water characteristics in the second,

TABLE 2
The Mean Absolute Error (MAE) (standard deviation in brackets) for the uncalibrated and calibrated Saxton-Rawls method for estimating the volumetric soil water content at saturation (SAT), field capacity (FC), and permanent wilting point (PWP) for the four soil data sets. Values are in per cent

Data set*	Estimates	SAT	FC	PWP	Mean
1	Uncalibrated	18.7 (12.0)	17.6 (17.3)	21.3 (19.9)	19.2
	Calibrated	14.4 (10.3)	15.3 (14.3)	18.1 (18.9)	16.0
2	Uncalibrated	28.1 (7.6)	20.6 (7.8)	34.9 (11.7)	27.9
	Calibrated	10.3 (6.6)	11.4 (7.0)	21.0 (11.3)	14.2
3	Uncalibrated	16.4 (9.8)	16.8 (20.2)	23.3 (18.3)	18.8
	Calibrated	11.0 (7.8)	15.5 (13.1)	18.4 (14.0)	15.0
4	Uncalibrated	20.6 (14.5)	29.5 (20.1)	43.3 (44.3)	31.1
	Calibrated	15.8 (10.4)	22.4 (14.6)	47.2 (45.0)	28.5

* Data set no. 1, 2, 3, and 4 are from Maene *et al.* (1983), Maesschalck *et al*. (1983), Teh (1996), and Hamdan *et al*. (1999), respectively

third, and fourth data sets. The validation tests revealed that the calibrated method remained stable and was still more accurate than the uncalibrated method (Table 2). The calibrated method, as compared to the uncalibrated method, had lower MAEs for estimating the soil water content at saturation, field capacity, and permanent wilting point. Additionally, as compared to the uncalibrated method, the calibrated method had lower standard deviations for MAE, denoting a smaller spread or variability of the estimation errors for the calibrated method. The calibration also reduced the mean MAE by 49, 20, and 8% in the second, third, and fourth data sets, respectively, as compared to that without any calibration.

All the results so far indicated that the calibrated method was more accurate than the uncalibrated method. One exception to this trend was the lower accuracy of the calibrated method (than the uncalibrated method) to estimate the soil water content at the permanent wilting point in the fourth data set (Table 2). Nonetheless, the overall accuracy of the calibrated method was still higher than the uncalibrated method in the fourth data set, albeit to a lesser extent of 8% as compared to 16, 20, and 49% in the other three data sets.

Soil water characteristic is a function of soil texture and structure (Gardner, 1973), particularly bulk density, particle size, mineral and organic composition, as well as pore-space density and distribution (Janik *et al.*, 2007). Despite requiring information only on the soil texture and organic matter, the Saxton-Rawls method has been shown to be reasonably accurate for over 1700 different soil types found in USA (Saxton and Rawls, 2006). Nevertheless, the present study revealed that it was necessary to calibrate the Saxton-Rawls method to improve its estimation accuracy for mineral soils of Malaysia. Without calibration, the mean estimation error (i.e., the mean MAE for all the four data sets) by the Saxton-Rawls method was 24%. With calibration, however, its mean error was reduced to 18%.

CONCLUSIONS

Based on the findings of the study, calibrating the Saxton-Rawls method was found to be necessary to increase its accuracy in estimating the soil water characteristics for the mineral soils of Malaysia. The Saxton-Rawls method was tested on a wide range of particle size distribution of the Malaysian mineral soils. The results showed that without calibration, the Saxton-Rawls method had a higher mean estimation error of 24%, as compared to only 18% with calibration. When compared to that without calibration, the calibrated Saxton-Rawls method estimated the soil water content at saturation, field capacity, and permanent wilting point, with a higher accuracy, and an average between 8 to 49%.

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