Comparing the Applicability of Soil Water Retention Models

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Abstract: Recently, the public has become more aware of the environmental problems facing our planet today. Underground water pollution is one of these problems, and it requires serious attention. As a result, many studies have been performed to examine the movement of water within soil. These studies present many new models for determining soil water retention rates. It is essential that these models be investigated for accuracy and applicability. This study attempts to analyze three of these well-known water retention models: Campbell, Saxton, and Huston-Cass. To analyze these models, the pressure plate test (ASTM C199-09) was performed on soil samples with different soil textures and from different geographical locations within the country of Iran. Using these results, the general applicability of each model was measured using the 1:1 slope line correlation method. In addition, the accuracy and applicability of each model was measured by calculating the Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE) for major samples with different soil textures. The results indicate that the Huston-Cass model is the most applicable for predicting soil water retention rates regardless of soil texture. Further results show that the Campbell model is more applicable relative to the Saxton model with regards to loamy soil. The Saxton model shows low accuracy and applicability, and should therefore only be used in cases where a high level of accuracy in the estimating process is not essential, or in cases with high pressure or suction terms.

Key-Words: Model Applicability, Pressure Plate Test, Site Investigations, Soil Water Retention Models

1 Introduction

Measuring the hydraulic properties of soil is an essential process that can be applied to many fields. For instance, hydraulic conductivity of the soil is an important factor for consideration when designing landfill areas, as this knowledge can help prevent contaminants leaching into the soil and polluting underground water. Therefore, accurate measurements of the hydraulic properties of soil can prove vital.

One of the most important aspects of soil hydrology is water retention [1], and many studies have been performed regarding this concept. Numerical modeling of water flow and solute transport in porous media often necessitates a simple analytical function for representation of the relationship between water content and matric suction with a water retention curve. Usually, a mathematical function is chosen, and its parameter values are determined by a regression analysis on the available data [2]. Various functions that describe the water retention curve are in use, such as those by Brooks and Corey [3] and van Genuchten [4]. Generally, these models are successful when analyzing soils with medium and high water content, but give poor results at low water content levels [5-7]. These models would therefore be ill-suited for certain applications, such as wetlands studies or evaluation of humid regions [8].

A study by Kern [9] evaluated some water retention models by applying various soil matric water pressures in order to identify minimum input data requirements. This study determined the Saxton model to be the most effective. Additionally, [10] the study investigated how inaccuracies present in water retention curves affect the hydraulic properties of soil and the computation of plant-available water. It was determined that errors in the water retention curve affect simulations of water flow and solute transport where these hydraulic properties are needed.

Modelling water retention is important, as laboratory tests are not always possible due to limitations of time and instrument availability. The goal of this study is to find the best and most applicable model for determining water retention rates by comparing and contrasting model results with those derived from standard pressure plate laboratory tests [11]. This study also aims to investigate the most applicable models for specific soil textures.

For this study, the pressure plate test was performed using three major soil samples with different textures and from different geographical locations within Iran. The results from these tests were then compared with estimations generated by the water retention models of Campbell, Saxton, and Huston-Cass.

2 Review of Soil Water Retention Curve Models

2.1 The Campbell Model

The Campbell model is given by equation 1 [12]:

$$\theta = \begin{array}{ll} \theta_s & \text{if } |\Psi| \le |\Psi_e| \\ \theta_s \left(\frac{\Psi_e}{\Psi}\right)^{-\frac{1}{b}} & \text{if } |\Psi| > |\Psi_e| \end{array} \tag{1}$$

where Ψ (m-H_2O) is the water potential, Ψ_e (m-H_2O) is the air-entry potential, θ ($m^3 H_2O m^{-3}$) is the volumetric water content, θ_s ($m^3 H_2O m^{-3}$) is the saturated volumetric water content, and b is a shape parameter related to the pore size distribution of the porous medium [10].

2.2 The Saxton Model

The Saxton et al. model [13] is given by equation 2:

$$\Psi = A\theta^B \tag{2}$$

where Ψ(kPa) is the matric potential, θ($m^3 H_2O m^{-3}$) is the volumetric water content, and A is a shape parameter related to the pore size distribution of the porous medium [9].

2.3 The Huston-Cass Model

The Huston-Cass model, with a correction suggested by Ross et al. [7], is given by equation 3:

$$\theta = \begin{cases} \theta_s \left(1 - c\left(\frac{\Psi}{\Psi_e}\right)^2\right) & \text{if } |\Psi| \le |\Psi_e| \\ \theta_s \left(\left(\left(\frac{\Psi_e}{\Psi}\right)^{-\frac{1}{b}} - \left(\frac{\Psi_e}{\Psi_d}\right)^{-\frac{1}{b}}\right) + a \ln \frac{\Psi_d}{\Psi}\right) & \text{if } |\Psi_d| \ge |\Psi| > |\Psi_e| \end{cases} \tag{3}$$

where all parameters are the same as defined for the Campbell model. *a* is the Ross correction coefficient, *c* is the Huston-Cass coefficient [14] and Ψ_d(m-H_2O) is the finite value of suction when $\theta = 0$ [15]. This model is also known as the modified Campbell model.

3 Materials and Methods

Samples were taken from suburban areas of three Iranian cities: Karaj (35°50′08″N 51°00′37″E), Neishabour (36°12′48″N 58°47′45″E) and Bushehr (28°58′N 50°50′E). These regions were selected due to their differing types of natural soil, and because the soil texture from these sites is representative of soil texture found anywhere in Iran. A mechanical drill auger was used to extract virgin samples from three surface depth ranges: 0 – 40 cm, 40 – 80 cm, and 80 – 120 cm. A total of 30 samples from each region were extracted, and the mean percentages of sand, loam, and clay were used to determine soil texture.

Water retention data was gathered using the ASTM C-1699-09 test [11], the standard test for pressure plates. For this test, pressure was applied to the saturated samples at the rates of 5, 33, 100, 500, and 1500 kPa. The samples were then dried in an oven at temperatures between 105 and 110 °C. Water content, bulk density, and volumetric water content were then calculated at each pressure (Table 1). This data shows that the samples from Karaj, Neishabour, and Bushehr composed mostly of sand, loam, and clay.

By plotting the amount of pressure versus volumetric water content it is possible to compare the soil water retention models with the results derived from the standard test for pressure plates. Furthermore, the calculated Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) have been used as indicators for comparing the models.

4 Results and Discussions

The data were plotted in relation to a 1:1 slope line to show the correlation between water content calculations derived from each model (estimated data) and results from the pressure plate tests (observed data). These graphs were plotted for all three water retention models. Figure 1 presents data from the Karaj soil samples, and shows the correlation of observed data with estimated data from each water retention model. The same method and discussion can be done for the Neishabour and Bushehr samples.

The Huston-Cass model shows the strongest correlation, as can be seen in the graph on the top left. The Campbell model shows an acceptable level of correlation, especially when compared to the Saxton model, which only shows acceptable levels of correlation in situations involving high pressure and suction.

Table 1. Physical Properties of Soil Samples

Region	**Karaj**	**Neishabour**	**Bushehr**
Percentage of Sand	39.98	38.76	29.66
Percentage of Loam	34.12	40.03	35.62
Percentage of Clay	08.14	19.04	40.83
Percentage of Organic Carbon	00.53	00.62	01.30
Bulk Density (ρ_b (gr/cm^3))	01.52	01.48	01.50
Water Content for Pressure = 5kPa (θ_5(%))	40.50	33.33	45.97
Water Content for Pressure = 33kPa (θ_{33}(%))	29.33	25.55	32.59
Water Content for Pressure = 100kPa (θ_{100}(%))	24.62	21.69	26.87
Water Content for Pressure = 500kPa (θ_{500}(%))	19.58	15.70	21.21
Water Content for Pressure = 1500kPa (θ_{1500}(%))	14.68	11.26	18.55

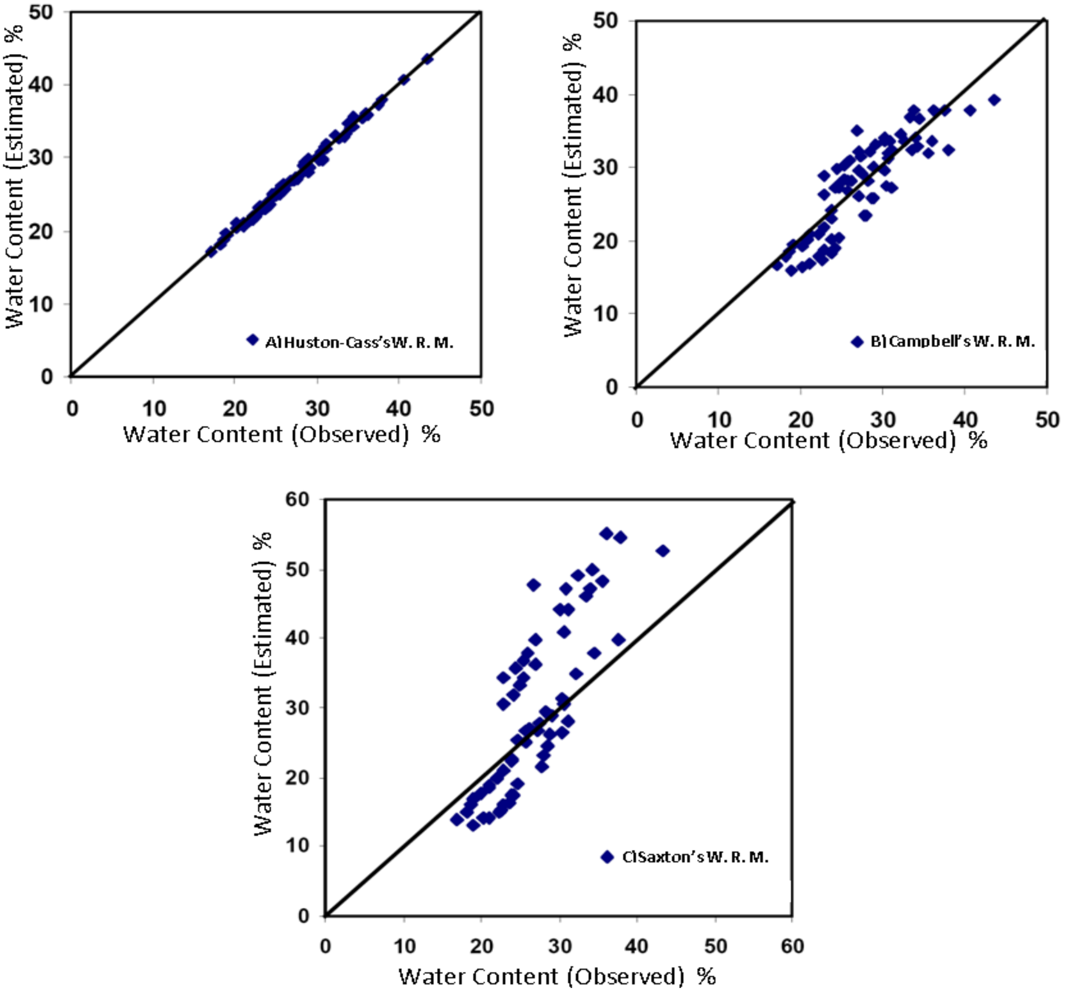

Figure 1. Comparison Plots for Estimated and Observed Water Content for Each Water Retention Model: a. Huston-Cass, b. Campbell and c. Saxton's Water Retention Model for Karaj

Table 2. Statistical Error Analysis for Samples with Different Texture

Water Retention Model	**Karaj (Sand)**		**Neishabour (Loam)**		**Bushehr (Clay)**	
	MAE (%)	**RMSE (%)**	**MAE (%)**	**RMSE (%)**	**MAE (%)**	**RMSE (%)**
Huston-Cass	-0.38	1.621	-0.02	1.220	0.48	1.084
Campbell	1.80	11.956	0.62	10.896	3.84	12.691
Saxton	7.20	29.446	6.19	25.140	-10.07	30.996

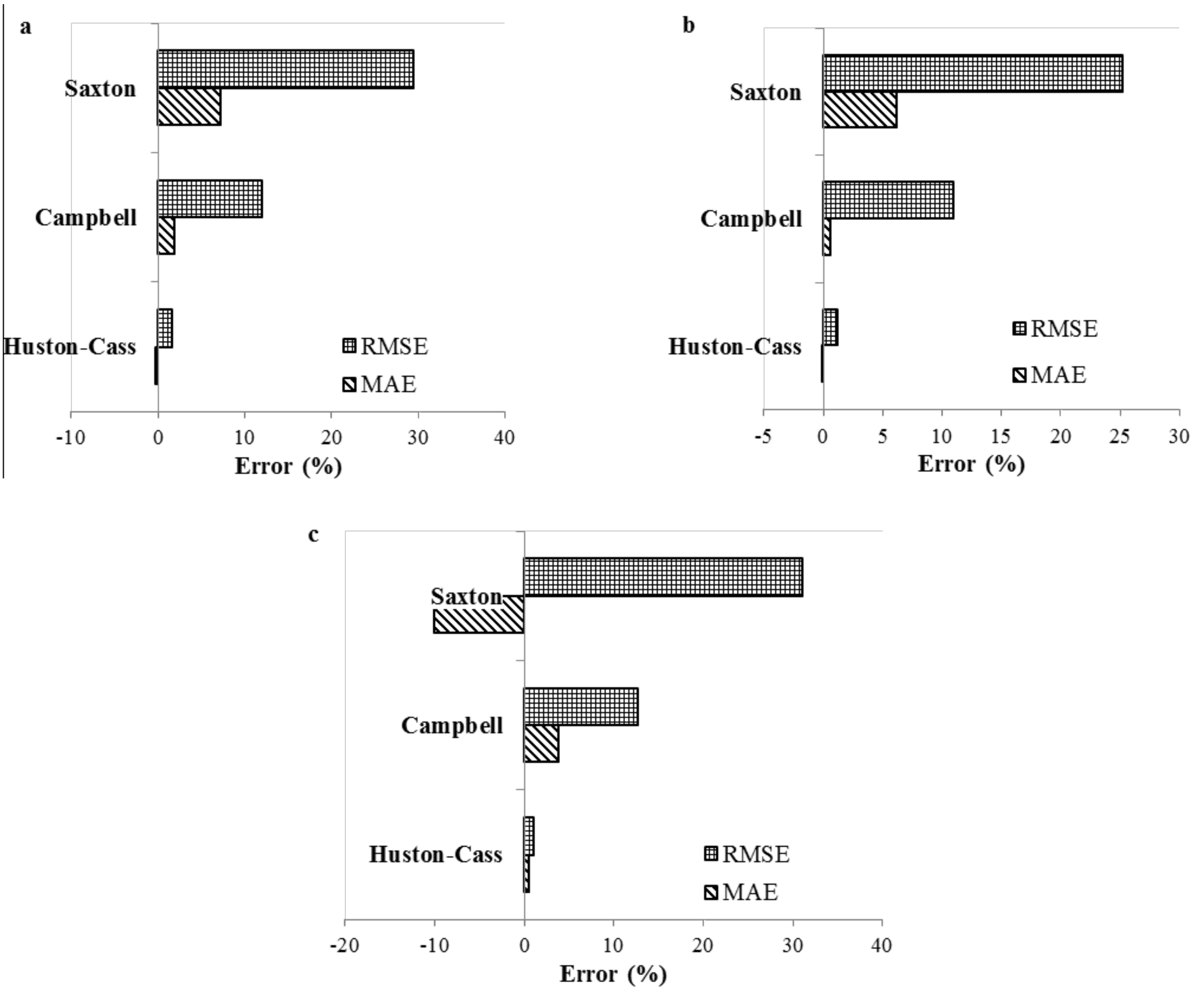

Figure 2. Comparative Graph for RMSE and MAE a. Karaj (Sand) b. Neishabour (Loam) and c. Bushehr (Clay)

Table 2 shows the RMSE and MAE as calculated for each major sample. These serve as further indicators of the correlation between estimated and observed water content data, and help to demonstrate the applicability of each model based on soil texture.

Figure 2 presents a graphical comparison of the RMSE and MAE for each model. From these graphs, it can be seen that the Huston-Cass model is most applicable regardless of soil texture. The Campbell model is also acceptable for soil composed primarily of loam, as seen in the Neishabour samples. The Saxton model showed a low level of accuracy, and is therefore only recommended for studies that do not require high levels of accuracy in water retention estimates. Use of the Saxton model for soil of majority clay composition is not recommended.

5 Conclusion

Results derived from the three models examined in this study are not always consistent with observed data obtained from the pressure plate test. The most applicable model for water retention estimation produces the most accurate estimates based on correlation and error analysis between the estimated and observed data. 1:1 slope line correlation shows that the Huston-Cass model is the most applicable, while the Saxton model is the least applicable, especially with regards to clay-based soil. The Saxton model can, however, be used for preliminary studies, or when a high level of accuracy is not necessary.

Statistical error analysis also shows the Huston-Cass model to be the most applicable, regardless of soil texture. As demonstrated by the RMSE, all models overestimate water content levels. In clay-based soil, the MAE showed overestimates produced by the Huston-Cass model, and underestimates resulting from the Saxton model.

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