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Evaluation of Several Dielectric Mixing Models for Estimating Soil Moisture Content in Sand, Loam and Clay Soils

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Abstract. *As part of a NOAA-funded project, studies are being conducted at the University of Puerto Rico-Mayagüez Campus using surface-based ground penetrating radar (GPR) to measure soil moisture content. The GPR will eventually be used to verify values of soil moisture at several locations in Puerto Rico using active radar and passive satellite-based sensors. As a part of the estimation process, it is necessary to relate moisture content to the GPR-measured dielectric constant. The motivation for this study was the need to select an appropriate dielectric mixing model for the wide range of soils being considered in the study. An important requirement of the dielectric mixing model was that it works well with input data available from NRCS Soil Survey Reports (e.g., soil texture, available water capacity, etc). The advantage of using this type of data is that it can be readily incorporated into a geographic information system (GIS) to be used with the geo-referenced dielectric data of the surface and satellite-based sensors.*

This paper provides a review of several dielectric mixing models, and compares moisture content estimates for sand, loam and clay soils, based on dielectric data obtained from a GPR, TDR and Theta Probe™. These results are also compared to soil moisture contents obtained from gravimetric data. Soils were characterized in terms of their chemical and physical properties; information needed by several of the dielectric mixing models. In some cases, especially with the loam soil, wide variations in the dielectric constants and moisture contents were observed.

Keywords. GPR, TDR, Theta Probe, dielectric constant, mixing model, moisture content.

Introduction

The practitioner is faced with two significant dilemmas when estimating soil moisture content with time domain reflectometry (TDR) and ground penetrating radar (GPR) instruments. 1) The various equipment available frequently operate at different frequencies and require instrument-specific procedures for deriving the dielectric constant from the reflected signal; and 2) After the dielectric constant has been obtained, it is necessary to calculate the volumetric soil moisture content using one of the numerous mixing model equations available in the literature, or perform a soil-specific calibration. Some commercially available equipment (e.g., Theta Probe) performs the dielectric determination and conversion to moisture content internally making it invisible to the user. The purpose of this study was to review several of the available mixing models and to compare estimates of soil moisture content derived from dielectric constants obtained from several instruments (GPR, TDR and Theta Probe) and soil types (sand, loam and clay).

Factors affecting a soil's dielectric constant include moisture content, soil texture, specific surface area, bulk density and instrument frequency. The most important influence on the dielectric constant of a soil is its water content. The dielectric constant for dry soil is approximately 4, whereas that of pure water is 81 (Wang and Schmugge, 1980). As soil texture changes from sand (coarse grain) to clay (fine grain), or soil organic matter increases, the soil's specific surface area increases, resulting in a greater percentage of bound water. The dielectric constant associated with this water decreases relative to free water. Wang and Schmugge, (1980) assigned a dielectric value to the bound water phase equal to that of ice (dielectric constant equal to 3.2 as compared to 81 for free water). Bulk density has been shown to have a strong influence on dielectric constant. Dirksen and Dasberg (1993) developed a family of dielectric/moisture content curves for bulk densities ranging from 0.6 to 1.55 g/cm^3. The effect of the bulk density has to do with the increased influence of the dielectric constant of the solid phase. Increasing bulk density resulted in increased dielectric constants. The transmitted electromagnetic wave frequency of the instrument has been shown to influence the magnitude of the dielectric constant for a given value of the moisture content (Benedetto and Benedetto, 2002). The dielectric constant of water decreases with increasing frequency above 1 GHz (Hallikainen et al.,1985). Other factors which can influence the dielectric constant include: geometric properties (Benedetto and Benedetto, 2002), temperature (Rassam and Williams, 2000), and electrochemical interactions (Benedetto and Benedetto, 2002).

Numerous dielectric mixing models have been developed during the last twenty-five years. Several dielectric mixing models for relating dielectric constant to moisture content were evaluated for use in this study, including: Topp et al., 1980; Alharthi and Lange, 1987; Miller and Gaskin, 1999; Benedetto and Benedetto, 2002; Hallikainen et al., 1985; and Wang and Schmugge, 1980.

The equation given by Topp et al. (1980), relating the apparent dielectric constant (ε) to the volumetric water content (θ_v) is given as:

$$\theta_v(\varepsilon) = -5.3\text{x}10^{-2} + 2.92\text{x}10^{-2}\,\varepsilon - 5.5\text{x}10^{-4}\,\varepsilon^2 + 4.3\text{x}10^{-6}\,\varepsilon^3 \qquad (1)$$

The above equation is empirical and does not account specifically for the soil properties, instrument frequency, or dielectric constants of the soil constituents (i.e., water, air and solids). The apparent dielectric constant can be calculated from knowledge of the dielectric constants of the individual soil components (water, air and solids) using the following equation (Alharthi and Lange, 1987):

$$\varepsilon(\theta_v) = \left[\phi_1\cdot(1 - s(\theta_v))\cdot\sqrt{\varepsilon_a} + \phi_1\cdot s(\theta_v)\cdot\sqrt{\varepsilon_w} + (1 - \phi_1)\cdot\sqrt{\varepsilon_s}\right]^2 . \qquad (2)$$

where s is the degree of saturation equal to zero when θ_v equals zero and 1 when θ_v equals the soil porosity.

The mixing model presented by Miller and Gaskin (1999) is used to convert the dielectric constant measured by the Theta Probe to volumetric moisture content, and has the following form:

$$\theta_v = \frac{\left(\sqrt{\varepsilon} - a_o\right)}{a_1} \qquad (3)$$

where a_o and a_1 are constants. Miller and Gaskin (1999) provide values of a_o and a_1 for “mineral soil” as 1.6 and 8.4, respectively; and the values for “organic soil” as 1.3 and 7.7, respectively.

Benedetto and Benedetto (2002) presented dielectric/moisture content data for sand and pozzolana at 0.6 and 1.6 GHz. The study only investigated moisture contents in the range of 0 to 20%. By interpolating the 0.6 and 1.6 GHz curves, it was possible to derive a curve for 1.5 GHz. This curve is expressed mathematically in the following equation. It should be noted that it is not advisable to use the following equation for soils in which the moisture content is above around 20%.

$$\varepsilon(\theta_v) = 91.589\cdot\theta_v^{\,2} + 17.007\cdot\theta_v + 3.0547 . \qquad (4)$$

The empirical model of Hallikainen et al. (1985) accounts for frequency and soil texture. The following equation is applicable to dielectric data collected at frequencies equal to 1.4, 6, 8 10 12, 14, 16 and 18 GHz, depending on the values of the parameters used.

$$\varepsilon(\theta_v) = (a_o + a_1\cdot S + a_2\cdot C) + (b_o + b_1\cdot S + b_2\cdot C)\cdot\theta_v + (c_o + c_1\cdot S + c_2\cdot C)\cdot\theta_v^{\,2} . \qquad (5)$$

where a_o, a_1, a_2, b_o, b_1, b_2, c_o, c_1 and c_2 are constants, S is percent of sand and C is percent of clay. For 1.4 GHz, the values of a_o, a_1, a_2, b_o, b_1, b_2, c_o, c_1 and c_2 were 2.862, -0.012, 0.001, 3.803, 0.462, -0.341, 119.006, -0.500, 0.633, respectively. (Note that a_o and a_1 in the above equation are not the same parameters used in the model of Miller and Gaskin;1999).

Wang and Schmugge (1980) presented a set of equations which accounts for soil texture, bulk and particle density, and wilting point. In this model, the parameter, W_t, is defined as the transition moisture content at which the dielectric constant increases steeply with increasing moisture content. Consequently two equations ($\varepsilon_1(\theta_v)$, and $\varepsilon_2(\theta_v)$) are necessary to define the moisture content/dielectric relationship within the moisture content range of 0 to 0.5:

$$\varepsilon_1(\theta_v) = \theta_v \cdot \varepsilon_{x1}(\theta_v) + (\phi - \theta_v) \cdot \varepsilon_a + (1 - \phi) \cdot \varepsilon_s \qquad \theta_v \le W_t \qquad \text{(6a}$$

with

$$\varepsilon_{x1}(\theta_v) = \varepsilon_i + (\varepsilon_w - \varepsilon_i) \cdot \frac{\theta_v}{W_t} \cdot \gamma$$

$$\gamma = -0.57 \cdot WP + 0.481$$

$$WP = 0.06774 - 0.00064 \cdot S + 0.00478 \cdot C \qquad W_t = 0.49 \cdot WP + 0.165$$

$$\varepsilon_2(\theta_v) = W_t \cdot \varepsilon_{x2} + (\theta_v - W_t) \cdot \varepsilon_w + (\phi - \theta_v) \cdot \varepsilon_a + (1 - \phi) \cdot \varepsilon_s \qquad \theta_v > W_t \qquad \text{(6b}$$

with

$$\varepsilon_{x2} = \varepsilon_i + (\varepsilon_w - \varepsilon_i) \cdot \gamma$$

where θ_v = volumetric moisture content, ε_1 = apparent dielectric constant for moisture content less than or equal to W_t, ε_2 = apparent dielectric constant for moisture content greater than W_t, ε_a = dielectric constant of air (1), ε_i = dielectric constant of ice (3.2), ε_w = dielectric constant of pure water (81), φ = porosity, WP = moisture content at the wilting point (pore water pressure = 15 bars), S = sand content in percent of dry soil, C = clay content in percent of dry soil, W_t = transition moisture content at which the dielectric constant increases steeply with increasing moisture content, and γ = fitting parameter which is related to WP.

Methods

Several “sandbox” experiments were conducted in the Soil and Water Laboratory of the Department of Agricultural and Biosystems Engineering, University of Puerto Rico-Mayagüez Campus (Harmsen and Parsiani, 2003 and Parsiani et al., 2003). Air dried soil was wetted 24 hours before the experiment so that the moisture content was two to three times greater than the air-dried soil. The wet and dry soil was placed in layers approximately 20 cm thick within the sand box. Metal rods (5/8 inch diameter) were place at the bottom of each soil layer to serve as a reflector of the GPR signal. Figure 1 show the “sandbox” setup.

The GPR device used in this research was a GSSI SIR-20 with a bow-tie transmit/receive antenna operating at 1.5 GHz. The depth resolution in sand is about 10 inches. Reflections are obtained at the boundary of two media of sufficiently different dielectric constants. Reflectors were laid at different depths to receive sharper reflections and be able to measure relative velocity wit ections of the GPR off of the reflectors is

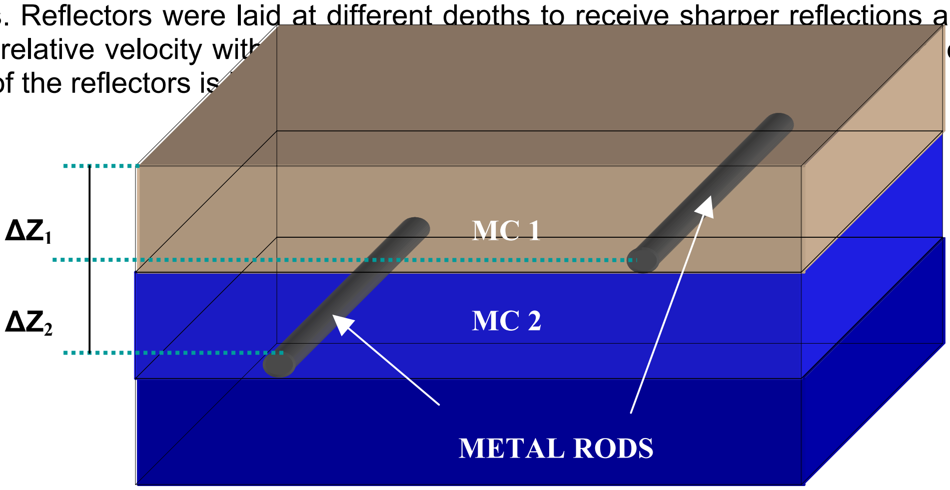

Figure 1. Schematic drawing of the "sandbox" configuration. MC 1 and MC 2 are moisture contents for layers 1 and 2, respectively. ΔZ_1 and ΔZ_2 are the thicknesses of layers 1 and 2, respectively (Parsiani and Harmsen, 2003).

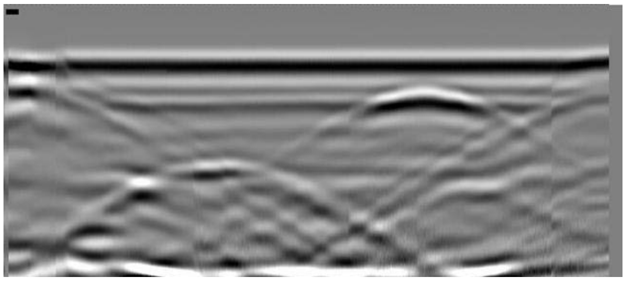

Figure 2. GPR image of the sand with metal reflectors

A Tektronix 1502 time domain reflectometer (TDR) was used to estimate the soil dielectric constant for comparison with estimates of the GPR. The instrument is able to precisely locate and analyze discontinuities in metallic cabling. However, in this research, measuring the dielectric constant of soil is accomplished by use of a wave guide, of length 20 cm, which is pushed into the soil. Figure 3 shows a picture of the 1502 TDR unit and a typical wave guide.

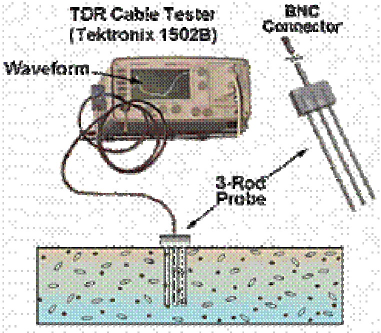

Figure 3. TDR device & its application

Dielectric constants were also determined using a Theta Probe (Miller and Gaskin, 1999). With this instrument, a standing wave measurement is made to determine the impedance of a sensing rod array from which the dielectric constant can be determined. Volumetric moisture content is then calculated using equation 3. Soil moisture was measured directly with the Theta Probe using the "mineral soil" setting, after which the dielectric constant was calculated by rearranging equation 3. The resulting dielectric constant was then used with the other mixing models.

The soils were analyzed for their chemical and physical properties by Soilcon Laboratories, Ltd. of British Columbia, Canada. The sand was construction sand (no name), the loam soil was San Antón Loam from Juana Diaz, PR, and the clay soil was Daguey Clay from the Finca Alzamora on the UPR Campus in Mayagüez, PR.

Results and Discussion

A comparison of the dielectric mixing models is presented in this section. Table 1 lists the required input required by each of the six models evaluated. Three of the models solve for dielectric constant as a function of the moisture content and three solve for the moisture content as a function of the dielectric constant.

Figure 4 compares the six mixing models graphically. For those models that required soil information, the data for sand was used. Table 2 lists the physical and chemical properties for the three soils used in this study. Figure 4 also provides the dielectric/moisture content data for sand obtained by the TDR, in which the moisture content was obtained by the gravimetric method (Harmsen and Parsiani, 2003). Under around 15% moisture content, all of the models compare well with the measured data, except the Hallikainen model. At high moisture contents, four methods seriously under predicted the dielectric constant, while the Wang and Schmugge and the Hallikanainen models performed well. It is interesting to note that only these two models require information regarding soil texture (Table 1).

Table 1. Dielectric mixing models compared in this study and there required input.

Method	ε	θ_v	f	ρ_b	ρ_s	ϕ[1]	% Clay	% Sand	WP	ε_i	ε_w	ε_a	ε_s
Topp (1980)	IV	DV											
Alharthi and Lange (1987)	DV	IV		√	√	√					√	√	√
Miller and Gaskin (1999)	IV	DV											
Benedetto and Benedetto (2002)	IV	DV	√										
Hallikainen et al. (1985)	DV	IV	√				√	√					
Wang and Schugge (1980)	DV	IV		√	√	√	√	√	√	√	√	√	√

Definitions: IV is independent variable, DV is dependent variable, ε is apparent dielectric constant, θ_v is the volumetric moisture content, f is frequency, ρ_b is bulk density, ρ_s is particle density, ϕ is porosity, % Clay is the percent of clay content, % Sand is the percent of sand content, WP is the wilting point, and ε_i, ε_w, ε_a and ε_s are the dielectric constants of ice, water, air and solids, respectively.

[1] If ρ_b and ρ_s are available then ϕ can be calculated from the relation: $\phi = (1 - \rho_b / \rho_s)$.

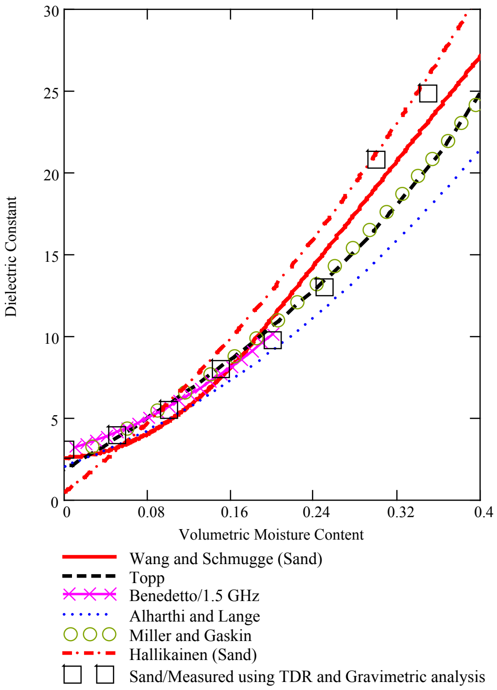

Figure 4. Comparison of the six mixing models which relate dielectric constant to the volumetric moisture content. Measure data is also provided for sand obtained using a TDR and gravimetric analysis.

Figure 5 compares the two models that account for soil texture (i.e., the Wang and Schmugge and Hallikainen models) for sand, loam and clay. Soils data were obtained from Table 2. Although the Wang and Schmugge model includes a method of estimating the wilting point from the percent sand and clay, it did not work well, and therefore we used the laboratory measured value of the wilting point directly. For clay at low moisture contents, the Hallikaninen model actually decreases slightly, which appears to be physically unrealistic.

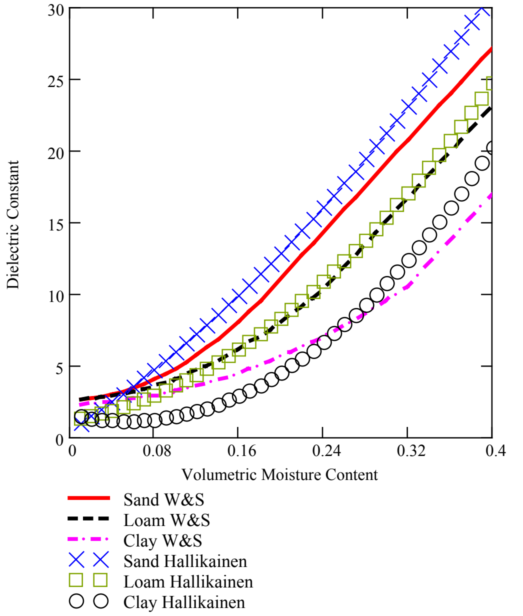

Figure 5. Comparison of the Wang and Schmugge (W&S) and Hallikainen dielectric mixing models for sand, loam and clay soils.

Tables 3, 4 and 5 contain the volumetric moisture content estimates for the sand, loam and clay soils. Dielectric constants for wet and dry soil were obtained by the GPR, TDR and Theta Probe, except in the case of the sand, in which the Theta Probe was not available during the time of the experiment. Table 6 summarizes the “best” and “worst” performing mixing models relative to the volumetric moisture content as determined by gravimetric analysis. There was no clear “best” mixing model, however, the Miller and Gaskin method appeared the most number of times in the “best” column. Furthermore it appeared only one time in the “worst” column, and in that case the error was under 5% (4.7%). Although this model ranked highest, its performance for the loam soil was disappointing. In the “worst” column, the model of Hallikainen appears eight out of sixteen times. This method only appeared one time in the “best” column with an error of 7.5%.

Table 2. Chemical and Physical Properties of the soils used in this study (Soilcon Laboratories, Ltd).

Analysis	**Parameter**	**Units**	**Sand**	**Loam**	**Clay**
	pH	pH units	7.27	6.44	4.65
	EC	(dS/m)	0.17	0.39	0.18
Total Carbon	TC	%	0.22	1.59	1.75
AmmoniumNitrogen	NH4	mg/kg	<1	5.31	2.31
Nitrate & Nitrite	Nitrogen	mg/kg	1.35	28.98	12.73
Total Nitrogen	TKN	%	0.12	0.14	0.30
Available P	Bray P	mg/kg	<0.6	11.73	7.02
Sulphate	S	mg/kg	7.90	18.00	21.00
Available Boron	B	mg/kg	<0.1	0.40	0.30
	Ca	mg/kg	2930.00	3150.00	869.57
Available Nutrients (NH4OAc Extractable)	K	mg/kg	<2	134.42	150.31
	Mg	mg/kg	160.64	450.72	263.58
	Na	mg/kg	8.85	64.64	15.71
	Cu	mg/kg	<0.03	3.61	3.42
Available Metals (0.1N HCl Extractable)	Fe	mg/kg	4.60	58.06	30.21
	Mn	mg/kg	23.79	76.59	19.88
	Zn	mg/kg	0.11	2.78	1.20
Cation Exchange Capacity		meq/100g	4.15	12.61	12.84
Exchangeable Cations					
	Ca	meq/100g	2.80	13.37	3.58
	Mg	meq/100g	0.50	3.55	2.55
	K	meq/100g	0.16	1.04	0.59
Total Organic Carbon	TOC	%	0.05	1.54	1.67
Texture	Sand	%	96.00	35.99	3.61
	Silt	%	1.56	39.53	29.06
	Clay	%	1.62	23.87	67.27
USDA Classification			Sand	Loam	Clay
Soil Characteristic Data	5 J/kg	% by vol	9.31	46.94	47.83
(Pressure vs. % Vol.)	10 J/kg	% by vol	6.86	39.52	46.12
	33 J/kg	% by vol	5.32	29.68	43.23
	70 J/kg	% by vol	4.77	26.41	41.56
	100 J/kg	% by vol	4.54	24.91	40.60
	300 J/kg	% by vol	3.95	20.92	37.20
	500 J/kg	% by vol	3.60	19.27	35.65
	800 J/kg	% by vol	3.27	17.90	34.14
	1200 J/kg	% by vol	2.93	16.73	32.52
	1500 J/kg	% by vol	2.71	15.80	31.43
Bulk Density		kg/m3	1387.80	1350.97	1092.38
Particle Density		kg/m3	2673.17	2533.14	2537.36
Total Porosity		% vol	48.08	46.66	56.95
Air Entry Tension		J/kg	0.00	3.87	0.72
Saturated Hydraulic Conductivity		cm/hr	65.70	0.24	2.77
Aeration Porosity	5 J/kg	% by vol	38.77	-0.27	9.12
Aeration Porosity	10 J/kg	% by vol	41.23	7.15	10.83
Available H20 Storage Capacity		% by vol	2.61	13.88	11.79

Table 3. Volumetric moisture content for sand estimated from GPR and TDR dielectric constants using six mixing model methods. Volumetric moisture content derived from gravimetric data is also shown.

SAND SOIL		Dielectric Mixing Model						
	Measured Dielectric Constant	Topp	Alharthi and Lange	Miller and Gaskin	Benedetto and Benedetto	Hallikainen et al.	Wang and Schmugge	Gravi-metric
		Moisture Content (% by volume)						
Dry	2.4/GPR	2.5	2.0	0.0	BC	4.6	7.0	7.0
Wet	9.0/GPR	15.5	19.7	16.7	15.0	13.7	27.2	21.0
Dry	3.1/TDR	6.1	4.3	1.9	7.0	5.0	14.8	7.0
Wet	6.7/TDR	19.3	14.7	11.8	20.7	11.3	31.4	21.0

Table 4. Volumetric moisture content for loam soil estimated from GPR, TDR and Theta Probe™ dielectric constants using Wang and Schmugge (W&S), Topp and Benedetto mixing models. Volumetric moisture content derived from gravimetric data is also shown.

LOAM SOIL		Dielectric Mixing Model						
	Measured Dielectric Constant	Topp	Alharthi and Lange	Miller and Gaskin	Benedetto and Benedetto	Hallikainen et al.	Wang and Schmugge	Gravi-metric
		Moisture Content (% by volume)						
Dry	4.6/GPR	6.7	9.0	6.5	7.7	12.0	11.4	2.4
Wet	6.6/GPR	13.8	14.4	11.5	11.1	17.1	16.8	24.6
Dry	4.6/TDR	6.9	9.0	6.5	7.5	12.0	11.6	2.4
Wet	7.5/TDR	13.7	16.4	13.6	13.0	18.6	19.0	24.6
Dry	5.6/TP	9.4	11.7	9.1	9.5	14.8	14.6	2.4
Wet	10.7/TP	20.2	23.0	19.9	22.0	23.8	24.5	24.6

TP is Theta Probe

Table 5. Volumetric moisture content for clay soil estimated from GPR, TDR and Theta Probe™ dielectric constants using Wang and Schmugge (W&S), Topp and Benedetto mixing models. Volumetric moisture content derived from gravimetric data is also shown.

CLAY SOIL		Dielectric Mixing Model						
	Measured Dielectric Constant	Topp	Alharthi and Lange	Miller and Gaskin	Benedetto and Benedetto	Hallikainen et al.	Wang and Schmugge	Gravi-metric
		Moisture Content (% by volume)						
Dry	2.8/GPR	2.5	3.0	1.0	BC	15.5	7.0	7.0
Wet	8.3/GPR	15.5	18.3	15.3	15.0	26.7	27.2	21.0
Dry	4.2/TDR	6.1	8.0	5.4	7.0	19.2	14.8	7.0
Wet	10.2/TDR	19.3	22.1	19.1	20.7	29.3	31.4	21.0
Dry	5.6/TP	9.4	11.7	9.1	9.2	22.2	19.6	7.0
Wet	11.3/TP	27.6	24.2	21.0	NA	30.7	32.8	21.0

TD is Theta Probe

Table 6. Best and worst performance by mixing models as compared to the volumetric moisture content determined by the gravimetric method.

Soil/Instrument/Wetness	**Best**	**Gravimetric minus Best**	**Worst**	**Gravimetric minus Worst**
SAND/GPR/DRY	Wang and Schmugge	0.0	Miller and Gaskin	7.0
SAND/GPR/WET	Alharthi and Lang	1.3	Hallikainen	7.3
LOAM/GPR/DRY	Miller and Gaskin	4.1	Hallikainen	-9.6
LOAM/GPR/WET	Hallikainen	7.5	Benedetto	13.5
CLAY/GPR/DRY	Wang and Schmugge	0.0	Hallikainen	-9.6
CLAY/GPR/WET	Alharthi and Lang	2.7	Benedetto	11.6
SAND/TDR/DRY	Benedetto	0.0	Wang and Schmugge	-7.8
SAND/TDR/WET	Benedetto	0.3	Wang and Schmugge	-10.4
LOAM/TDR/DRY	Miller and Gaskin	-4.1	Hallikainen	-9.6
LOAM/TDR/WET	Wang and Schmugge	5.6	Benedetto	11.6
CLAY/TDR/DRY	Benedetto	0.0	Hallikainen	-12.2
CLAY/TDR/WET	Benedetto	0.3	Wang and Schmugge	-10.4
LOAM/Theta Probe/DRY	Miller and Gaskin	6.7	Hallikainen	-12.4
LOAM/Theta Probe/WET	Wang and Schmugge	0.1	Miller and Gaskin	4.7
CLAY/Theta Probe/DRY	Miller and Gaskin	-2.1	Hallikainen	-15.2
CLAY/Theta Probe/WET	Miller and Gaskin	0.0	Hallikainen	-9.7

In general, all models performed poorly for the loam soil (except estimates based on the dielectric constant from the Theta Probe/wet soil). Soil chemical properties can help explain unusual values of dielectric constant, however, in this case the loam had relatively low electrical conductivity (0.39 dS/m), and it total organic carbon (TOC) and cation exchange capacity (CEC) were roughly equivalent to the clay (Table 2). Additional investigation is needed to help explain the poor results for the loam soil. From this study, unfortunately, it is not possible to specify the best mixing model to use under the wide set of soil conditions that may be encountered when employing a satellite based sensors.

Summary and Conclusion

This paper presented a comparison of six dielectric mixing models for use with time-domain dielectric data. Dielectric data obtained from “sandbox” studies using a GPR, TDR and Theta Probe were obtained for wet and dry sand, loam and clay. Physical and chemical property data for the three soils was presented. As compared to the volumetric moisture content determined by the gravimetric method, the Miller and Gaskin model (a_o and a_1 parameters for “mineral” soil) performed best. Although this model ranked highest, its performance for the loam soil was disappointing, as was the case for all other models. Additional study is needed in the proper usage of the models as applied to the loam soil.

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