Modeling Available Soil Moisture

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Both the amount and the availability of water in soil is important to plant roots and soil dwelling organisms. To describe the amount of water in the soil we use the term water content. To describe the availability we talk of water potential. In thermodynamics the water content would be referred to as the extensive variable and the water potential as the intensive variable. Both are needed to correctly describe the state of water in soil and plants. In addition to describing the state of water in the soil, it may also be necessary to know how fast water will move in the soil. For this we need to know the hydraulic conductivity. Other important soil parameters are the total pore space, the drained upper limit for soil water, and the lower limit of available water in a soil. Since these properties vary widely among soils, it would be helpful to establish correlations between these very useful parameters and easily measured properties such as soil texture and bulk density. This chapter will present the information needed for simple models of soil water processes.

Water Content and Bulk Density

The amount of water in soil is described as the water content. This can be described on either a mass or a volume basis. The mass basis water content is the mass of water lost from a soil sample when it is dried at 105 °C divided by the mass of the dry soil. This definition is useful for determining the water content in the laboratory, but is not particularly useful for describing the amount of water in the field. There, the volume basis water content is more useful. It is the volume of water held in unit volume of soil. If w is the mass basis water content and θ is the volume basis water content, then

$$\theta = \frac{w\rho_b}{\rho_w} \qquad (1)$$

where ρ_b and ρ_w are the bulk density and the density of water. The bulk density of the soil is the dry soil mass divided by the soil volume. The water density is 1 Mg/m^3. In mineral soils the bulk density typically has a value between 1.1 and 1.7 Mg/m^3. The volumetric water content is therefore typically larger than the mass water content.

You can think of θ as the fraction of the soil volume taken up by water. The fraction taken up by solids can be computed from the bulk density:

$$f_s = \frac{\rho_b}{\rho_s} \qquad (2)$$

where ρ_s is the density of the soil solids. It typically has a value around 2.65 Mg/m^3. The total pore space in the soil is $1 - f_s$. When the soil is completely saturated with water, its water content is the saturation water content, ρ_s. It can be calculated from the bulk density as:

$$\theta_s = 1 - f_s = 1 - \frac{\rho_b}{\rho_s} \qquad (3)$$

Water Potential

All water held in soil is not equally available to plants, microbes and insects. One measure of availability is the water potential. Water potential is the potential energy per unit mass of water of the water. The water in the soil is held by forces of adhesion to the soil matrix, is subject to gravitational attraction, and contains solutes which lower its energy compared to the energy of pure, free water. Living organisms must therefore expend energy to remove water from the soil. The water potential is a measure of the energy per unit mass of water which is required to remove an infinitesimal quantity of water from the soil and transport it to a reference pool of pure free water. Because energy is usually required to remove water, water potential is usually a negative quantity. For potential energy per unit mass, the units of water potential are 3 2 J/kg. Energy per unit volume comes out J/m^3, or N/m or Pa. We strongly favor J/kg, but one frequently sees water potential reported in kPa or MPa. One J/kg is numerically almost equal to 1 kPa.

While many factors influence the water potential, the most important in a biological context is usually the matric potential. It arises because of the attraction of the soil matrix for water, and is therefore strongly dependent on the properties of the matrix and the amount of water in the matrix. Figure 5.1 shows typical moisture release curves or moisture characteristics for sand, silt and clay soils. Clays, because of their smaller pore sizes and greater particle surface areas, lower the water potential more at a given water content, than do sands and loam soils. Moisture characteristics like those in Fig. (1) are linear when the logarithm of water potential is plotted as a function of the logarithm of water content. The equation describing these curves is:

$$\psi_m = \psi_c \left(\frac{\theta}{\theta_s}\right)^{-b} \quad (4)$$

where ψ_m is matric potential, θ is volumetric water content, ψe is called the air entry potential of the soil, and b is a constant. The air entry potential and saturation water content are sometimes combined into a single constant a, giving

$$\psi_m = a\theta^{-b} \quad (5)$$

so $$a = \psi_e \theta_s^{\,b} \quad (5.5)$$

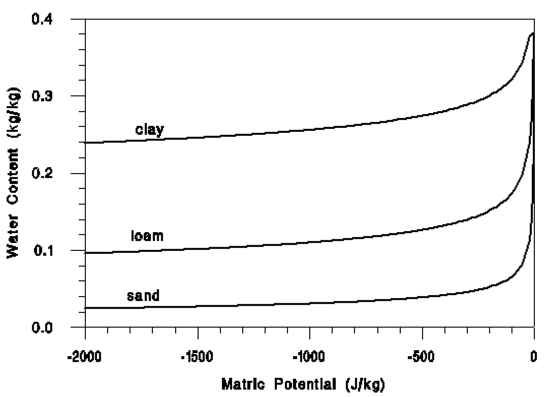

Figure 1 Soil moisture characteristic for three different soil types

The air entry potential and the b value depend on the texture and structure of the soil. Soil texture can be specified using the name of a textural class, such as silt loam or fine sandy loam, as fractions of sand, silt and clay, or as a mean particle diameter and a standard deviation of particle diameters. The latter is the most useful for determining hydraulic properties. We will use the bulk density or total pore space as a measure of soil structure.

Shiozawa and Campbell (1991) give the following relationships for converting measurements of silt and clay fractions to geometric mean particle diameter and standard deviation:

$$d_g = \exp(5.756 - 3.454\, m_t - 7.712\, m_y) \quad (6)$$

and

$$\sigma_g = \exp\{[33.14 - 27.84\, m_t - 29.31\, m_y - (\ln d_g)^2]^{1/2}\}$$

where m_t and m_y are the fractions of silt and clay in the sample, d_g is the geometric mean particle diameter in µm, and σ_g is the geometric standard deviation.

The relationships between hydraulic properties and the soil texture and structure are, at present, quite uncertain, even though a lot of research has been done in this area. The following are equations derived partially from theory and partially by empirically fitting data sets from a number of locations. The dependence of air entry potential on texture and bulk density can be computed from:

$$\psi_e = \frac{-5}{\sqrt{d_g}}\left[2\left(1-\frac{\rho_b}{\rho_s}\right)\right]^{-b} = \frac{-5}{\sqrt{d_g}}(2\theta_s)^{-b} \quad (7)$$

where θ_s is from eq. 3 and d_g is from eq. 6.

The exponent, b can be estimated from

$$b = \frac{10}{\sqrt{d_g}} + 0.2\sigma_g \quad (8)$$

Table 1 lists the 12 texture classes of soils and gives the approximate silt and clay fractions for the center of each class. It then shows the values for d_g, σ_g, ψe, and b for each class.

Field Capacity and Permanent Wilting Point

Water moves rapidly through soil at high water content, mainly because of the downward pull of gravity and the high hydraulic conductivity of nearly saturated soil. As water drains from the soil, however, the hydraulic conductivity decreases rapidly and the rate of movement slows. The downward movement of water under the influence of gravity becomes very small at water potentials between -10 and -33 J/kg. Water at potentials below these values is therefore held within the root zone and is available for plant uptake. The water content when the matric potential is between -10 and -33 J/kg (-10 for sands; -33 for clays) is the field capacity water content (θ_{fc}), or the drained upper limit. This is the water content one would expect to find if a soil profile were wet by a heavy rain or irrigation, covered, and allowed to stand for two or three days. In other words, it is the highest water content one would typically expect to find in a field soil except right after water is added.

Values of the water content at -33 J/kg were computed using eq. 4 for each of the textures, assuming ρ_s = 0.5, and are shown in Table 1. Note that sands drain to just a few percent moisture at field capacity, while finer texture soils may have water contents above 0.3 m^3 m^{-3}. Note, however, that all field capacity water contents are well below saturation. The values shown in the table may need to be adjusted to represent what one would find in the field because the bulk density tends to be texture dependent. Sands tend to have high bulk densities (1.6 Mg/m) while finer textured soils tend to have lower bulk densities.

Permanent wilting does not mean that the plant is killed by water potentials in this range. It means that the plant will not recover from wilting unless water is applied. Many species are able to withdraw water from soil to water potentials well below -1500 J/kg, and rapid withdrawal of water from the soil will make water unavailable to the plant which is held at potentials well above -1500 J/kg. The value does, however, provide an approximate lower limit for the water content of soil from which plants are extracting water. Values of θ_{pwp} are also shown in Table 1 for θ_s = 0.5.

Plant available water is defined as the water held in the soil between field capacity and permanent wilting. These values are also shown in Table 1. The values are low for coarse- textured soils, but

Table 1 Physical and hydraulic properties of soils according to soil texture. The silt and clay fractions are mid-range values for each textural class. The hydraulic properties were computed using the equations from the text assuming θ_s = 0.5 for all textures.

Texture	*Silt*	*Clay*	d_g (μm)	σ_g	ψ_e (J/kg)	*b*	k_s (kg s m^{-3})	θ_{-33} (m^3 m^{-3})	θ_{-1500} (m^3 m^{-3})	θ_{av} (m^3 m^{-3})
Sand	0.05	0.03	210.96	4.4	-0.34	1.6	0.00211	0.03	0.00	0.03
Loamy sand	0.12	0.07	121.68	8.7	-0.45	2.7	0.001217	0.10	0.02	0.08
Sandy loam	0.25	0.10	61.62	12.2	-0.64	3.7	0.000616	0.17	0.06	0.11
Sandy clay loam	0.13	0.27	25.14	28.6	-1.00	7.7	0.000251	0.32	0.19	0.12
Loam	0.40	0.18	19.81	16.4	-1.12	5.5	0.000198	0.27	0.14	0.14
Sandy clay	0.07	0.40	11.35	40.0	-1.48	11.0	0.000113	0.38	0.27	0.11
Silt loam	0.65	0.15	10.53	9.6	-1.54	5.0	0.000105	0.27	0.13	0.14
Silt	0.87	0.07	9.12	4.1	-1.66	4.1	9.12e-05	0.24	0.10	0.15
Clay loam	0.34	0.34	7.09	23.3	-1.88	8.4	7.09e-05	0.36	0.23	0.13
Silty clay loam	0.58	0.33	3.34	11.4	-2.73	7.7	3.34e-05	0.36	0.22	0.14
Silty clay	0.45	0.45	2.08	13.9	-3.47	9.7	2.08e-05	0.40	0.27	0.13
Clay	0.20	0.60	1.55	23.0	-4.02	12.6	1.55e-05	0.42	0.31	0.11

tend to be quite uniform for other soil textures, even though the field capacity and permanent wilting point values vary widely. A note of caution is in order though in using the values given in the table.

Predicting PWP from Field Capacity

Since both field capacity and permanent wilting point can be computed from basic soil parameters, it stands to reason that they would be correlated. Figure 2 shows the permanent wilt water content for all 12 texture classes plotted as a function of the field capacity water content. The correlation is good, and the data are fit well by a second order polynomial. The practical outcome of this is that one needs only know one or the other of these variables, and the other can be found from the relationship between the two.

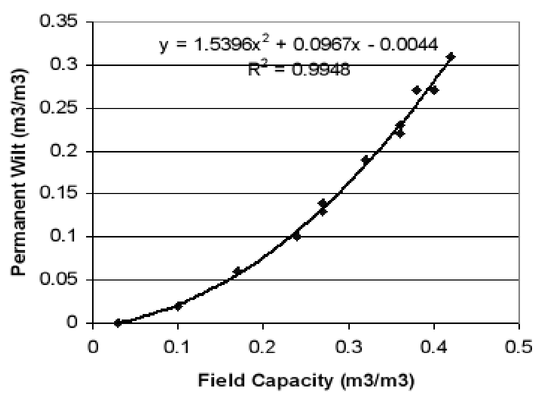

Figure 2 Permanent wilt water content as a function of field capacity water content for the 12 texture classes shown in Table 1.

Obtaining Hydraulic Properties from Soil Survey Data

The -33 and -1500 J/kg (1/3 and 15 bar) water contents are often available from soil survey data. If they are known, we can find a and b in eq. (5.5). Taking logarithms of both sides in eq. (5.5), we obtain ln ψm = ln a-b lnθ. Substituting θ_{fc} = 33 and θ_{pwp} = 1500, and their corresponding water contents (use positive numbers for ψm when you take logs; you can't take the log of a negative number) you get two equations in two unknowns, b and a, which you can solve simultaneously to get the two parameters:

$$b = \frac{\ln 1500 - \ln 33}{\ln \theta_{fc} - \ln \theta_{pwp}} \qquad (9)$$

$$a = \exp(\ln 33 + b \ln\theta_{fc}) \qquad (10)$$

Make sure the values of θ_{fc} and θ_{pwp} that you use are volumetric water content. Most laboratory data are mass basis water contents because they are measured using oven drying. If they are mass basis water contents, convert them to volume basis water contents using the bulk density and eq. 1 before using them to compute a and b. Sometimes all one has is an estimate of available water content ford a soil. In this case, we can estimate b sufficiently accurately to still find a value for a. Let θ_{av} = θ_{fc} - θ_{pwp}, be the available water content for the soil.

We can rearrange eq. (5) to obtain

$$a = \left(\frac{\theta_{av}}{\psi_{fc}^{-1/b} - \psi_{pwp}^{-1/b}} \right)^{b} \qquad (11)$$

If we have no other information to indicate the value for b, we will assume a value of 5. This gives $a = 6370\theta_{av}^{5}$. Knowing values for a and b, we can use eq. (5) to find θ_{fc} and θ_{pwp}. An estimate of air dry water content, which we will need in models of evaporation from soil surfaces, is estimated from

$$\theta_{d} = \frac{\theta_{pwp}}{3} \qquad (12)$$

References

1. Campbell, G. S. (1985) Soil Physics with BASIC: Transport Models for Soil-Plant Systems. Elsevier, Amsterdam.

2. Shiozawa, S. and G. S. Campbell (1991) On the calculation of mean particle diameter and standard deviation from sand, silt, and clay fractions. Soil Sci. 152:427-431

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