

# Soil–Water Terminology and Applications

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Two important expressions used to describe the state of water in the soil are *water content* and *water potential*.

## 4.1 WATER CONTENT

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Water content is a measurement of the amount of water in the soil either by weight or volume and is defined as the water lost from the soil upon drying to constant mass at 105°C ([Soil Science Society of America, 2008](#)). It is expressed in units of either mass of water per unit mass of dry soil (kg/kg) or in units of volume of water per unit bulk volume of soil ( $\text{m}^3/\text{m}^3$ ).

## 4.2 WATER POTENTIAL

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The second expression utilizes the potential energy status of a small parcel of water (say a milligram) in the soil. The expression applies also to a small parcel of water in a plant. All water in the soil (or plant) is subjected to force fields originating from four main factors: the presence of the solid phase (the matrix); the gravitational field; any dissolved salts; and the action of external gas or water pressure. If the force fields in the soil are compared with a reference point, then they can be expressed on a potential energy basis, and each of the four factors can be assigned a separate potential energy value. The sum of these four potential energy values is called the *water potential* of the soil or the *total water potential* to emphasize that it is comprised of several factors. The water potential is abbreviated using the Greek letter psi,  $\Psi$ . Subscripts are sometimes added to the letter:  $\Psi_w$  stands for water potential and  $\Psi_T$  stands for total water potential.

The reference point for these potential energies is taken as pure free water at some specified height or elevation. Because water is held in the soil by forces of adsorption, absorption, cohesion, and solution, soil water is usually not capable of doing as much work as pure free water. Hence the soil water potential is normally negative. The old term for soil water potential, no longer used, is the *total soil moisture stress* and it is defined using positive values.

We now describe each component of the water potential.

#### 4.2.1 Matric (Capillary) Potential, $\Psi_m$

The *matric potential energy* or the *matric potential* is the portion of the water potential that can be attributed to the attraction of the soil matrix for water. The matric potential used to be called the *capillary potential*, because, over a large part of its range, the matric potential is due to capillary action akin to the rise of water in small, cylindrical capillary tubes (Baver et al., 1972, p. 293). (In Chapter 6, we study in detail the rise of water in soil pores.) However, as the water content decreases in a porous material, water that is held in pores due to capillarity becomes negligibly small, when compared with the water held directly on particle surfaces. The term *matric potential*, therefore, covers phenomena beyond those for which a capillary analogy is appropriate.

The matric potential may be determined with a tensiometer, which measures matric potential of water in situ. (In Chapter 5, we shall describe tensiometers.) The word *tensiometer* refers to the fact that it measures the *soil moisture tension*, a term no longer used in defining the components of the water potential. Other old terms used to describe the matric potential are the *soil moisture suction* or the *matric suction*. As we shall see in Chapter 5, a tensiometer consists of a porous, permeable ceramic cup connected through a water-filled tube to a manometer, vacuum gauge, or other pressure measuring device. Water pressure in the manometer comes into equilibrium with the adjacent soil through flow across the ceramic cup. The height of the liquid column at that time is an index of matric potential. Soil moisture tension has been represented often with a positive sign, in which case it can be considered to be numerically equivalent to, but opposite in sign to, the matric potential.

The units used to measure matric potential, and other potentials, become evident when we consider measurement of matric potential with a tensiometer. The force per unit area, or negative pressure of the water in the porous cup, is the weight per unit cross section of the hanging column. This is the volume of the column divided by the area multiplied by the

density of the liquid water and the acceleration due to gravity (Baver et al., 1972, pp. 294–295):

$$P = F/A = mg/A = (V)(\rho_w)(g/A) = (hA\rho_w g)/A = h\rho_w g \quad (4.1)$$

where  $P$  = pressure;  $F$  = force;  $m$  = mass;  $g$  = acceleration due to gravity;  $A$  = area;  $V$  = volume;  $\rho_w$  = density of water;  $h$  = height, and the potential (negative pressure) is in units of potential energy or work per unit volume. In the centimeter-gram-second (CGS) system of units, 1020 cm of water would exert a negative pressure of

$$(1020 \text{ cm})(1 \text{ g/cm}^3)(980 \text{ cm/sec}^2) = 999,600 \text{ dyne/cm}^2 \quad (4.2)$$

or  $1 \times 10^6 \text{ dyne/cm}^2 = 1 \text{ bar}$ , because, in cgs pressure units,  $1 \text{ bar} = 1 \times 10^6 \text{ dyne/cm}^2$ . The SI (Système International) unit for pressure is the Pascal, which is  $1 \text{ N/m}^2$ , and thus 10 bars = 1 MPa or 1 MegaPascal. The unit ( $\text{dyne/cm}^2$ ) is the same as potential energy/volume, because if we multiply the top and bottom of the fraction,  $F/A$ , in Eqn (4.1) by 1 cm ( $=\text{cm/cm} = \text{unity}$ ), we get work/volume = potential energy/volume:

$$[(\text{dyne})(\text{cm})]/[(\text{cm}^2)(\text{cm})] = \text{potential energy/volume} = \text{erg/cm}^3,$$

because  $1 \text{ dyne cm} = 1 \text{ erg}$ .

Units of potential energy per unit volume can be converted to units of potential energy per unit mass by dividing by the density of water, which we shall take to be  $1 \text{ g/cm}^3$ :

$$\begin{aligned} (1 \times 10^6 \text{ dyne/cm}^2)/1 \text{ gram/cm}^3 &= 1 \times 10^6 \text{ dyne cm/gram} \\ &= 1 \times 10^6 \text{ erg/gram} = 100 \text{ joule/kg}, \end{aligned}$$

because  $1 \text{ J} = 1 \times 10^7 \text{ erg}$ . Or, 1 bar can be considered to be the equivalent of 100 J/kg. Note that the units of matric potential are not equal to potential energy units (ergs; joules), but can be given in units of potential energy/vol or potential energy/mass.

Note that in Eqn (4.1), if the acceleration due to gravity,  $g$ , were not constant, we could not equate pressure to a length unit. However, the acceleration due to gravity can be considered a constant on the earth. We can determine it using Helmert's equation (Weast, 1964, p. F-29):

$$g = 980.616 - 2.5928 \cos 2\varphi + 0.0069 \cos^2 2\varphi - 3.086 \times 10^{-6} H \quad (4.3)$$

where

$g$  = acceleration due to gravity in cgs units ( $\text{cm/s}^2$ ).

$\varphi$  = latitude.

$H$  = elevation (cm).

F.R. Helmert was the director of the Prussian Geodetic Institute. In 1915, Helmert introduced his equation to determine  $g$ , the acceleration due to gravity (Lambert, 1956).

Helmert's equation comes from the inverse square law of gravity or Newton's law of universal gravitation (Shortley and Williams, 1971, p. 61):

$$F = [G(m_1 m_2)]/R^2 \quad (4.4)$$

where

$F$  = gravitation force.

$m_1$  and  $m_2$  are masses of two particles.

$R$  = distance between the two particles.

$G$  = fixed proportionality constant = gravitation constant.

The units of  $G$  = (N m<sup>2</sup>)/kg<sup>2</sup> or m<sup>3</sup>/(kg s<sup>2</sup>).

Using the first set of units for  $G$ ,  $G = 6.67 \times 10^{-11}$  N m<sup>2</sup>/kg<sup>2</sup>.

In words, the principle of universal gravitation states that every particle of matter in the universe attracts every other particle with a gravitational force. The magnitude of the gravitational force between two particles is proportional to the product of the masses of the particles and inversely proportional to the square of the distance between them. The gravitational forces of attraction between two particles act along the line joining the two particles (Shortley and Williams, 1971, p. 61).

The following information comes from Don Kirkham (personal communication, February 6, 1992). The law of universal gravitation governs planets and satellites. We can imagine a mass at the center of the earth as the basis for the pull to the earth (the *center of mass*; also called the *center of gravity*; Shortley and Williams, 1971, p. 167). The pull depends upon where on the surface of earth we are, but this pull holds only if earth is static. However, the earth spins and this affects the pull. That is, how close we are to the axis (to the center of the earth) affects the pull. We can imagine ourselves spinning on a saucer or a wheel. We are thrown off differently if we are at the middle or tip of the wheel. If we are standing on the equator, we are thrown off more. The first cosine terms in Helmert's equation (first one to the right of the equal sign in Eqn (4.3)) relates to latitude. At the equator,  $\cos 0 = 1$ , and when we go up to the North Pole, we are at  $90^\circ$ . The earth spins toward the east, and we have to take this into consideration in Helmert's equation. The cosine term takes into account the Coriolis effect due to the earth's spin. The Coriolis effect is an apparent force, relative to the earth's surface, that causes deflection of moving objects to the right in the Northern Hemisphere and to the left in the Southern Hemisphere due to the earth's rotation. It is named for Gustav Gaspard de Coriolis (1792–1843), a French mathematician who published a quantitative mathematical work on the subject in 1835 (Glickman, 2000). As we get closer to the equator, the Coriolis effect gets

less. The other cosine term relates to the fact that the earth is not a perfect spheroid, but an ellipsoid. The earth bulges out at the equator. Height,  $H$ , affects gravity, too, because the further we are away from the center of mass, the less is the pull of gravity. Note we subtract the  $H$  term in Helmholtz's equation. We can calculate  $g$  for Manhattan, Kansas, which is 1065 ft (32,461 cm) above sea level and is at latitude  $39^{\circ}12'$  or  $39.2^{\circ}$ . We find that  $g$  for Manhattan, Kansas, is  $979.99475 \text{ cm/s}^2$ , which rounds off to  $980 \text{ cm/s}^2$ , the gravitational constant in the CGS system for the earth.

One might say, why bother with  $g$ ? We are bothering with  $g$  to show it is a constant, so Eqn (4.1) can be used to equate a pressure to a length. Even though the acceleration due to gravity is essentially a constant, variations in it are important in exploration for minerals. The concentration of many metals will change the period of a pendulum. A pendulum and  $g$  are related because the equation giving the frequency of oscillation of a pendulum includes  $g$ . (See Chapter 8 for definitions of frequency and period.) Therefore, the relation can be used to determine gravitational acceleration by measuring the frequency of a pendulum (Shortley and Williams, 1971, pp. 253–254). This method furnishes one of the most accurate means of measuring  $g$ .

#### 4.2.2 Gravitational Potential, $\Psi_g$ or $\Psi_z$

The *gravitational potential energy* or the *gravitational potential* is the potential energy associated with vertical position. The reference height or datum assigned can vary according to need and is often based on utility. It is generally convenient to keep the reference level sufficiently low so that one does not get negative values. Solutions to problems are prone to error when negative numbers are used. Land surveyors take their datum at a level below the lowest level that they expect to encounter on their survey to ensure that all of their levels will be positive. Soil scientists often take either the soil surface or the groundwater level as the reference level. The reference level usually depends on the direction of water movement: rising or infiltration. If the reference level is below the point in question, work must be done on the water and the gravity potential is positive; if the level is above the point in question, work is done by the water and the gravity potential is negative (Baver et al., 1972, p. 296).

#### 4.2.3 Solute Potential, $\Psi_s$

The *solute potential energy* or *solute potential* is the portion of the water potential that can be attributed to the attraction of solutes for water. If pure water and solution are separated by a membrane, pressure will build up on the solution side of the membrane that is equivalent to the energy difference in the water on the two sides of the membrane. This pressure,

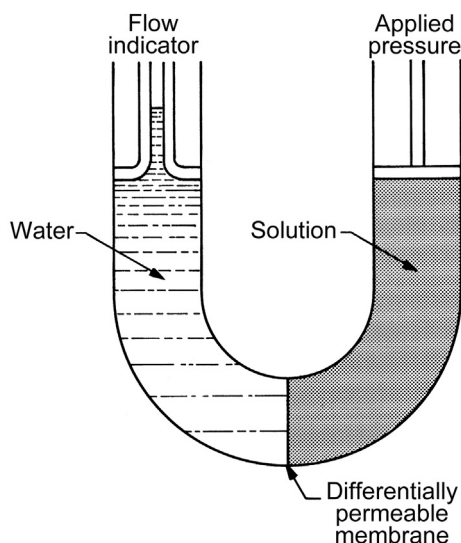


FIGURE 4.1 Diagram of an osmometer in which a membrane permeable to water but impermeable to a solution separates pure water from the solution. The osmotic pressure of the solution is equal to the pressure that must be applied to prevent movement of water into it. Water movement is observed by a change in the level of water in the capillary tube on the left. From *Kramer (1983)*. Reprinted by permission of Academic Press.

which is usually called the *osmotic pressure*, is numerically equivalent, but opposite in sign, to the solute potential. The solute potential in soil is often called the *osmotic potential*,  $\Psi_o$ , even if no membranes are present. The osmotic potential is usually ignored in determining water movement in the soil, unless the soil is saline. Osmotic potential is important in plants and is discussed in Chapter 17.

An osmometer is used to measure osmotic pressure (Figure 4.1). It consists of a U-tube that contains dissolved substances in solution on one side, which is separated from pure water in the other arm by a semi-permeable membrane at the bottom. The osmotic pressure of the solution is equal to the pressure that must be applied to prevent movement of water into it (*Kramer, 1983*, p. 18). The membrane must have openings that are large enough to permit passage of water molecules but too small for ions of the dissolved substance to pass through (*Baver et al., 1972*, p. 298).

#### 4.2.4 Pressure Potential, $\Psi_p$

The *pressure potential energy*, or *pressure potential*, is the potential energy due to the weight of water at a point under consideration, or to gas pressure that is different from the pressure that exists at a reference position (*Baver et al., 1972*, p. 297). Sometimes this pressure potential energy is divided into two separate components: the *air pressure potential*, which occurs under unsaturated conditions when the soil has an air phase, and the *hydrostatic pressure potential*, which occurs when the soil is saturated

and there is a hydrostatic pressure from an overlying water phase (Jury et al., 1991, p. 51). In saturated soil, the pressure potential is sometimes called the *piezometric potential* (Baver et al., 1972, p. 297), because it can be measured with a *piezometer*. A piezometer is an instrument used to measure pressure. The word comes from the Greek *piezein*, which means “to press”, and *meter*, which comes from *metron*, a measure (Webster’s New World Dictionary of the American Language, 1959). It is a tube placed in soil with its top end open to the atmosphere. It also may have openings in the wall at the point where the pressure measurement is to be taken. The level of water in the tube, measured from a suitable reference, is the piezometer reading. Piezometers are used to measure groundwater depth. Pressure potentials due to gas may be measured with manometers.

#### 4.2.5 Other Potentials Defined

Occasionally, a *tensiometer pressure potential*, which is the potential measured with a tensiometer, is defined (Jury and Horton, 2004, p. 54). The matric potential differs from the potential measured with a tensiometer, because the soil air pressure is maintained at the reference pressure. The reference pressure can be atmospheric pressure. However, the difference between atmospheric pressure and air pressure in the soil is usually ignored, and the potential measured with a tensiometer is considered to be the matric potential. But if one were comparing measurements of matric potential made with a tensiometer on top of a mountain and at sea level, then one would have to consider air pressure differences.

Other potentials may be defined according to need, such as an *overburden potential*, which occurs when the soil is free to move and some part of its weight becomes involved as a force acting upon water at the point in question (Baver et al., 1972, p. 299). Such an overburden potential might occur in soil under a ridge in a ridge-till system. But the pressure exerted by the weight of the soil in the ridge would be small. When a potential that is not zero is neglected, it must be assumed that it is implicitly included in one of those that is explicit in the definition. For example, when overburden potential is neglected, it becomes implicit in the pressure potential or matric potential.

In both soil and plant systems the water potential is usually considered to be the sum of the four potentials described in the preceding sections: matric potential, gravitational potential, solute potential (or osmotic potential), and pressure potential, or

$$\Psi = \Psi_m + \Psi_g + \Psi_s(\text{or } \Psi_o) + \Psi_p \quad (4.5)$$

Water moves in response to differences in water potential. The difference is called the *water potential difference*. The *water potential gradient* is the potential difference per unit distance of flow. Water moves from high

potential energy to low potential energy. Under nonsaline, unsaturated conditions, the two most important potentials in the soil are the matric potential and the gravitational potential, and both must be considered in determining the direction of flow of water. Under nonsaline, saturated conditions, the two most important potentials in the soil are the (hydrostatic) pressure potential and the gravitational potential, and the difference in the sum of these two potentials, called the *hydraulic head difference*, governs the soil water flow. In plants, the two most important components of the water potential are the osmotic potential and the pressure potential, also called the turgor potential (see Chapter 17).

### 4.3 HEADS IN A COLUMN OF SOIL

A head is a source of water kept at some height to supply, for example, a mill. Hence, it is a pressure, as in a *head* of steam ([Webster's New World Dictionary of the American Language, 1959](#)). Instead of using potential terminology, we can express potential in terms of head (a length). As we saw in [Eqn \(4.1\)](#), the tension, or negative pressure, that develops in a tensiometer is

$$F/A = h\rho_w g,$$

where  $F$  = force;  $A$  = area;  $h$  = height;  $\rho_w$  is the density of water; and  $g$  is acceleration due to gravity. Because the density of water and acceleration due to gravity are constants, we can relate a pressure or negative pressure, in terms of potential energy per unit volume, to a length. Engineers prefer to work with lengths (heads) rather than potentials because they are easier to measure and keep track of.

So our equation for water potential in soil, [Eqn \(4.5\)](#),  $\Psi = \Psi_m + \Psi_g + \Psi_s$  (or  $\Psi_o$ ) +  $\Psi_p$ , becomes in head terminology the following for a nonsaline soil ( $\Psi_s$  or  $\Psi_o$  is negligible):

$$h = h_t + h_g + h_p \quad (4.6)$$

where  $h$  = total head;  $h_t$  = tension head (we call it the tension head instead of the matric head);  $h_g$  = gravitational head; and  $h_p$  = pressure head.

Under saturated conditions when there is no tension head, the total head is

$$h = h_p + h_g.$$

When the soil is under tension (but the pores can be filled with water, i.e., saturated, yet the water is under tension, which we discuss in Chapter 6), we have

$$h = h_t + h_g.$$

or

$$h = (h_p \text{ or } h_t) + h_g.$$



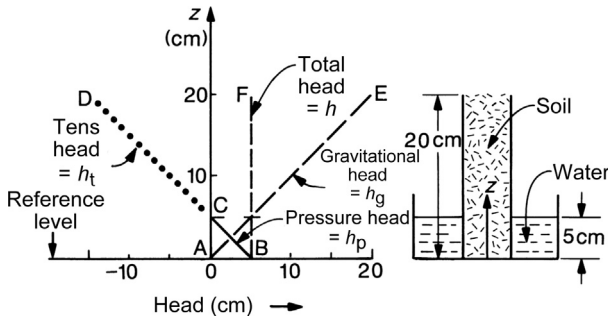


FIGURE 4.2 Heads in a column of wet soil. From Kirkham and Powers (1972). This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

The total head  $h$  is usually called the *hydraulic head*. Let us apply head terminology to determine heads in a column of soil. We follow the analysis of Kirkham and Powers (1972, pp. 36–37) and plot the four heads  $h$ ,  $h_g$ ,  $h_p$ , and  $h_t$  in a column of wet soil. (For a biography of W.L. Powers, see the Appendix, Section 5.) In Figure 4.2 we have plotted the various heads against distance  $z$  above the base of a soil column standing in 5 cm of water. The water in the column is assumed to be saturated to the top above the 5 cm level by capillarity and is at equilibrium. Evaporation from the top of the soil is prevented. The reference level for heads is the level of the base of the column. The line AE is a graph of height  $z$  versus gravitational head  $h_g$ ; the line BC is of  $z$  versus pressure head  $h_p$ ; CD is of  $z$  versus tension head  $h_t$ ; and BF is of  $z$  versus total head  $h$ . The line BF is vertical because at all heights  $z$  in the column the abscissas  $h_g$  and  $h_t$  (or  $h_p$ ) must add up to the same value  $h$ , the total head ( $=5$  cm). Otherwise, the water in the column could not be in equilibrium and the water would move. The equilibrium conditions for the column may be written symbolically as

$$h_g + h_p = h = 5 \text{ cm, for } z \text{ between } 0 \text{ cm and } 5 \text{ cm}$$

and

$$h_g + h_t = h = 5 \text{ cm, for } z \text{ between } 5 \text{ cm and } 20 \text{ cm.}$$

The line BC in the graph shows that the pressure head decreases linearly from 5 cm of head to 0 cm of head as the height  $z$  increases from 0 to 5 cm. From  $z = 5$  cm to  $z = 20$  cm the pressure becomes negative; that is, tension develops. The tension at level E is 15 cm of water, a negative pressure. If evaporation were permitted at the soil surface, the tension head there would be of greater magnitude than 15 cm and curves CD and BF would change from their shown positions. In Figure 4.2 the tension head  $h_t$  is that resulting from water curvature in the pores, which we shall

discuss in Chapter 6. “Equivalent” tension heads obtained by indirect methods such as freezing-point depression do not reflect film curvature, and when such equivalent tension heads are plotted on a graph with tensions as measured by a tensiometer, the freezing-point-depression values may be three times as great in magnitude as the tensiometer values, and confusion may result (Kirkham and Powers, 1972, p. 37). The freezing-point method to determine the free energy of water in soil is described by Richards (1965, pp. 137–139).

In Figure 4.2, tension could be determined with a tensiometer for the distance of  $z$  between 5 and 20 cm, and pressure could be determined with a piezometer for the distance of  $z$  between 0 and 5 cm.

#### 4.4 MOVEMENT OF WATER BETWEEN TENSIOMETERS

Because we can equate pressure or negative pressure or tension with height, let us use height to determine the direction of movement of water in soil with two tensiometers. All we need is a ruler. Figure 4.3, as modified from Richards (1941) and reproduced by Kirkham and Powers (1984, p. 240), gives a physical picture of how the tension head  $h_t$  and the gravitational head  $z$  combine to give the total head  $h$ . Tensiometers are shown with water manometers inside of the soil. In actuality, the water manometers would be replaced by mercury manometers above the soil. The physical principles are clearer if the water manometers are

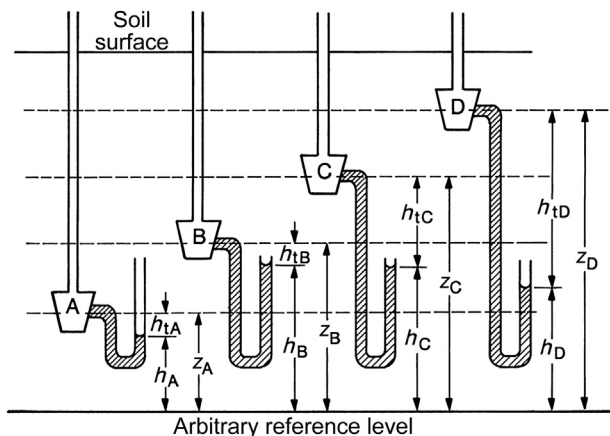


FIGURE 4.3 Diagram to illustrate water movement between tensiometers. From Kirkham and Powers (1984), ©1972, John Wiley & Sons, Inc.: New York. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

represented as shown. The reference level for head is taken at a depth  $z_D$  below the center of the uppermost tensiometer cup.

In Figure 4.3 we notice that for each location, A, B, C, and D, the total head is given by  $h = h_t + z$  (where  $h_t$  is negative). For location A and B,  $h_{tB}$  has been taken equal to  $h_{tA}$ . Thus, the soil moisture is of equal dryness at A and B; but this does not mean that the soil moisture will be statically held between A and B. On the contrary, since the total head  $h_B$  is seen to be greater than  $h_A$ , moisture will move from B to A. At locations C and B we see that  $h_{tC}$  has been taken to be more negative than  $h_{tB}$ . Thus, the soil is drier at C than at B, but moisture will not move from the wetter soil at B to the drier soil at C because we have chosen conditions such that the total head  $h_B$  is equal to  $h_C$ . Therefore, moisture neither moves from B to C nor from C to B; the moisture is in equilibrium. Finally, we note that moisture will move upward from C to D because our moisture conditions at points C and D have been chosen such that  $h_C$  is greater than  $h_D$ . However, we notice that because  $h_{tD}$  is more negative than  $h_{tC}$  (tension is greater for D than C), the soil at D has to be considerably drier than at C to cause the upward movement. In Figure 4.3, if the reference level were at the top of the figure, the values  $h_A$ ,  $h_B$ , and so on would always be negative;  $h_t$ , of course, is negative for unsaturated soil regardless of the location of the reference level (Kirkham and Powers, 1984, pp. 241–242).

## 4.5 APPENDIX: BIOGRAPHY OF WILLIAM L. POWERS

William LeRoy Powers is the son of LeRoy Powers, a geneticist and breeder of agronomic and horticultural crops, who worked for the Agricultural Research Service of the United States Department of Agriculture on the campus of Colorado State University in Fort Collins (Cattell, 1961). LeRoy Powers was a famous geneticist and excellent statistician (George L. Liang, personal communication, July 26, 2002), who published a classic paper in plant genetics (Powers, 1963). William Powers received his B.S. degree at Colorado State and joined the Department of Agronomy at Iowa State University in the fall of 1960 to pursue a master's degree and Ph.D. under Don Kirkham. He obtained his M.S. degree in 1962 and the Ph.D. in 1966; the title of his Ph.D. dissertation was "Solution of Some Theoretical Soil Drainage Problems by Generalized Orthonormal Functions". After he obtained his Ph.D. he moved to Kansas State University, where he rose through the academic ranks to professor and became Director of the Evapotranspiration Laboratory and Director of the Kansas Water Resources Research Institute. In 1980, he accepted the position of Director of the Water Resources Center at the University of Nebraska in Lincoln.

He wrote, with Don Kirkham, *Advanced Soil Physics* (Wiley: New York, 1972; reprint edition, 1984). His research included developing formulas

for applying organic wastes to soils; water-balance studies; pore-size distribution as an index of atrazine movement; tillage effects on soil water release curves; estimating soil water content from soil strength; 2,4,6-trinitrotoluene (TNT) sorption in soil; spatial series analysis of horizontal soil cores to characterize tracer patterns; physical and chemical characteristics of aging golf greens; and spatial analysis of machine-wheel traffic and its effects on soil physical properties.

He married in 1958, and he and his wife, Marty, a registered nurse, have two daughters, Jenny and Susan. He retired from the University of Nebraska on July 31, 2001, and spends his retirement doing volunteer work, including volunteering at the Veteran's Administration Hospital in Lincoln, Nebraska, and tutoring in the GED (general equivalency degree; it certifies that one has an educational level equivalent to a high school graduate) program at Southeast Community College in Lincoln, Nebraska.

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