

Pore Volume

Soil not only permits entry of water and nutrients and their storage there but also allows wasteful passage past roots. We have seen how with the tension infiltrometer we can measure mobility of solutes (see Section 13.9, Chapter 13). An older method to analyze movement of solutes through the soil is based on measuring pore volumes. This method does not divide the soil water into mobile, θ_m , and immobile, θ_{im} , regions, but considers the water in the soil to be the sum of both, the total volumetric water content, θ . By measuring pore volume, we consider the physical process of the movement of solutes in fluids (Kirkham and Powers, 1972, p. 380). It gives us information concerning what takes place in a porous medium as one fluid displaces another.

14.1 DEFINITIONS

The *Glossary of Soil Science Terms* (Soil Science Society of America, 2008) defines *pore volume* as “pore space”. And then the definition of *pore space* is given as follows: “The portion of soil bulk volume occupied by soil pores.” This is a valid definition of pore volume. We see the pore volume defined this way in Figure 12.1. Pores are filled with air or water. However, pore volume has another, special meaning in soil physical work. It is important to understand this meaning because pore volumes are widely determined when one is studying the movement of solutes (e.g., dissolved fertilizers or pollutants) through a soil. The term has been misapplied, so it is important to know how to calculate pore volumes.

First let us review definitions. From Darcy’s law, we remember that the quantity of flow Q (cm^3/h) is the volume of fluid passing through a porous medium in an hour. We also recall that the *Darcy velocity*, which we here shall abbreviate v_d in (cm/h), is the quantity of flow per cross-sectional area A of the flow medium; that is, v_d is Q/A . The Darcy velocity is sometimes called the *flux* (Kirkham and Powers, 1972, p. 400).

The *Glossary of Soil Science Terms* (Soil Science Society of America, 2008) defines *flux* as follows: “The time rate of transport of a quantity (e.g., mass or volume of fluid, electromagnetic energy, number of particles, or energy) across a given area. See also *flux density*.” The *Glossary* defines *flux density* as follows: “The time rate of transport of a quantity (e.g., mass or volume of fluid, electromagnetic energy, number of particles, or energy) per unit area perpendicular to the direction of flow.” Flux and flux density often are used interchangeably.

If we were passing water through a vertical soil column by placing a constant head of water on the soil surface, v_d would be the downward velocity of the surface of the water above the soil surface. The *average pore velocity*, v , is the velocity in (cm/h) per unit cross-sectional area (cm²) in the pore space. In terms of the Darcy velocity, the average pore velocity is given by

$$v = v_d / \alpha \quad (14.1)$$

where v_d is the Darcy velocity and α is the water-filled porosity of the flow medium (not to be confused with the α in Wooding’s equation—e.g., see Eqn (13.8)). Because α is always <1 , the average pore velocity will always be greater than the Darcy velocity (flux). This is logical because we would expect an element of water in the soil to move faster than the surface of the water standing over the soil (Kirkham and Powers, 1972, p. 400).

We also want to remember that the *actual velocity* of the water is on the average v/f , where f is the porosity. (See Eqn (7.2) for the equation to calculate porosity.) The actual velocity of the water in the soil is much greater than the Darcy velocity. The actual velocity, for Darcy’s law (saturated, no tension conditions), refers to water in soil that has all the pores completely filled with water. So there is no air-filled porosity. The average pore velocity can refer to completely saturated conditions when it is the actual velocity. But in most situations, we are dealing with unsaturated soil, so both air and water are in the pores, and α refers just to the water-filled porosity.

We are making a special point here to distinguish among the Darcy velocity, the actual velocity, and the average pore velocity because the literature often is not clear as to which velocity is being used in mathematical models. Readers should make sure that they know which velocity is being used (Kirkham and Powers, 1972, pp. 400–401).

14.2 ILLUSTRATION OF BREAKTHROUGH CURVES AND PORE VOLUMES

To analyze concentration changes of solute in the effluent from a soil column, we present the data in a standard form called a *breakthrough curve*.

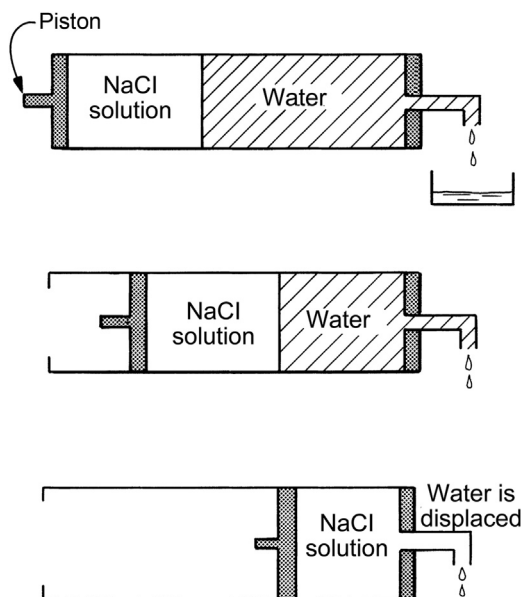


FIGURE 14.1 Schematic drawing of piston flow in a tube. From *Advanced Soil Physics* by Kirkham, D., Powers, W.L., p. 382, ©1972, John Wiley & Sons, Inc.: New York. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

A breakthrough curve is a plot of the ratio C/C_0 versus the number of pore volumes of effluent collected. Here C is the concentration of the solute found in the effluent (or leachate; we are not referring to wastewater effluent here, but the liquid that comes out of the bottom of a column of soil when it is leached). C_0 is the initial concentration of the solute in the displacing fluid, and the pore volume V_0 is the volume of the porous medium occupied by fluid (Kirkham and Powers, 1972, p. 381).

Figures 14.1–14.4 illustrate the different kinds of flow of a solute in solution through a medium. Figure 14.1 shows the piston flow for an NaCl

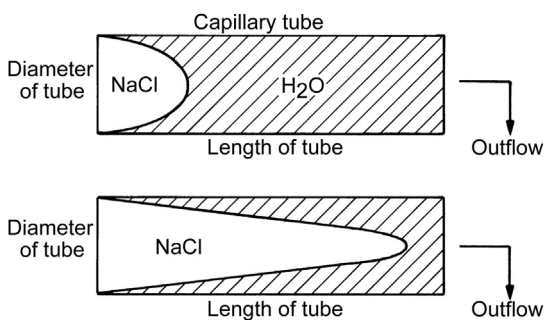


FIGURE 14.2 Schematic drawing of actual flow in a tube. From *Advanced Soil Physics* by Kirkham, D., Powers, W.L., p. 383, ©1972, John Wiley & Sons, Inc.: New York. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

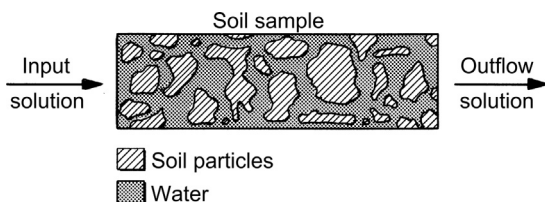


FIGURE 14.3 Schematic drawing of flow in a saturated soil. From *Advanced Soil Physics* by Kirkham, D., Powers, W.L., p. 384, ©1972, John Wiley & Sons, Inc.: New York. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

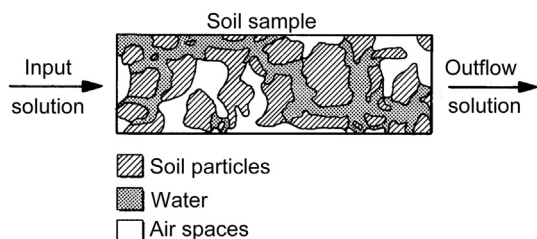


FIGURE 14.4 Schematic drawing of flow in an unsaturated soil. From *Advanced Soil Physics* by Kirkham, D., Powers, W.L., p. 384, ©1972, John Wiley & Sons, Inc.: New York. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

solution replacing water. Piston flow, in fact, is not a mixing process at all, but is a 100% displacement process as illustrated in the figure. Figure 14.2 shows the actual flow in a tube where an NaCl solution is invading water. Figure 14.3 shows the flow in saturated soil, and Figure 14.4 shows the flow in unsaturated soil (Kirkham and Powers, 1972, pp. 382–384). (The columns are all oriented horizontally because Kirkham and Powers are looking at transmission of water as it moves horizontally—i.e., gravity free, desk-top experiments.) The breakthrough curves for each of these four types of flow are shown in Figures 14.5–14.8. Figures 14.9 and 14.10 show the breakthrough curves for chloride in an Oakley sand and an Aiken clay loam, respectively, and Figure 14.11 shows the breakthrough

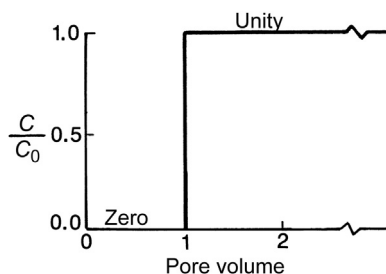


FIGURE 14.5 Breakthrough curve for piston flow. From *Advanced Soil Physics* by Kirkham, D., Powers, W.L., p. 385, ©1972, John Wiley & Sons, Inc.: New York. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

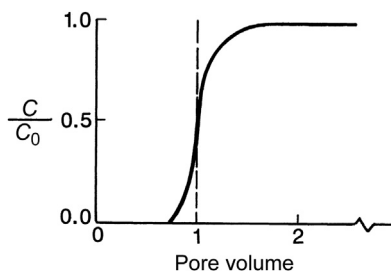


FIGURE 14.6 Breakthrough curve for flow in a tube. From *Advanced Soil Physics* by Kirkham, D., Powers, W.L., p. 385, ©1972, John Wiley & Sons, Inc.: New York. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

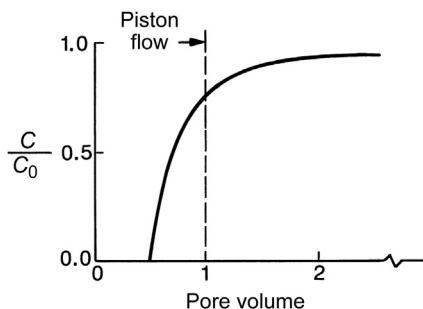


FIGURE 14.7 Breakthrough curve for wide range in pore velocities as in a saturated soil. From *Advanced Soil Physics* by Kirkham, D., Powers, W.L., p. 386, ©1972, John Wiley & Sons, Inc.: New York. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

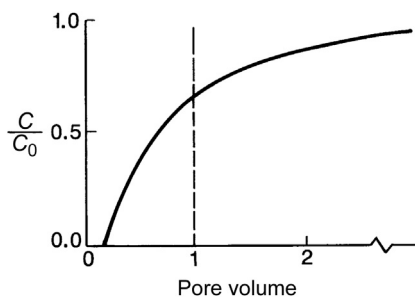


FIGURE 14.8 Breakthrough curve characteristic of an unsaturated soil. From *Advanced Soil Physics* by Kirkham, D., Powers, W.L., p. 386, ©1972, John Wiley & Sons, Inc.: New York. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

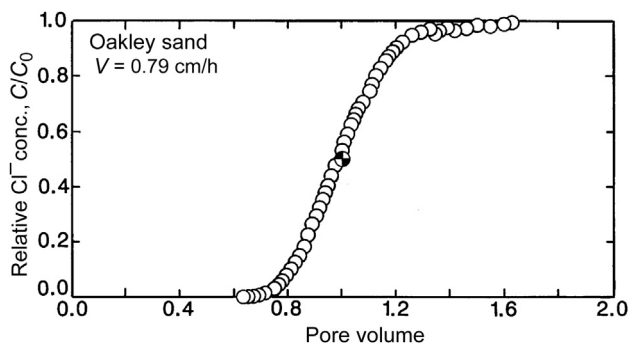


FIGURE 14.9 Chloride breakthrough curve for Oakley sand. The bicolor circle shows where 0.5 pore volume would occur. From *Advanced Soil Physics* by Kirkham, D., Powers, W.L., p. 387, ©1972, John Wiley & Sons, Inc.: New York. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

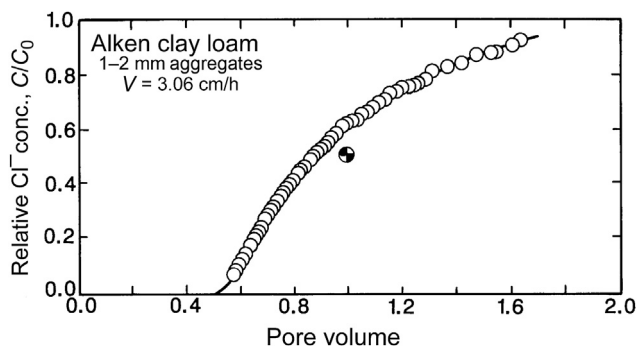


FIGURE 14.10 Chloride breakthrough curve for Aiken clay loam. The bicolor circle shows where 0.5 pore volume would occur. From *Advanced Soil Physics* by Kirkham, D., Powers, W.L., p. 387, ©1972, John Wiley & Sons, Inc.: New York. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

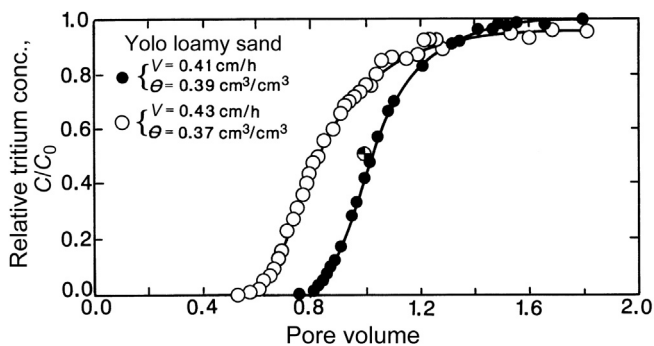


FIGURE 14.11 Tritium breakthrough curve for Yolo loamy sand at two different water contents. The bicolor circle shows where 0.5 pore volume would occur. From *Advanced Soil Physics* by Kirkham, D., Powers, W.L., p. 388, ©1972, John Wiley & Sons, Inc.: New York. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

curve for tritium in a Yolo loamy sand (Kirkham and Powers, 1972, pp. 385–388).

14.3 MATHEMATICAL ANALYSIS OF PORE VOLUME

A pore volume V_o is the volume of the porous medium in question occupied by fluid and may be defined by (Kirkham and Powers, 1972, p. 401)

$$V_o = \alpha V \quad (14.2)$$

where V is the bulk volume of the porous medium and α is the water-filled porosity, and we note that the right-hand side of Eqn (14.2) yields one pore volume. The number of pore volumes p of fluid passed through a medium in time t is equal to the volume Qt of fluid moved through the medium divided by its pore volume, that is,

$$p = Qt/V_o \quad (14.3)$$

which, on dividing the numerator and denominator by A , yields

$$p = [(Qt)/A]/[(\alpha V)/A] \quad (14.4)$$

In Eqn (14.4), we can substitute LA for V , where L is the length of the soil column, and we have $v_d = Q/A$. We can thus write

$$p = v_d t / \alpha L \quad (14.5)$$

Knowing the equation for average pore velocity, we can substitute v for v_d/α , and we can write Eqn (14.5) as

$$p = vt/L \quad (14.6)$$

Kirkham and Powers (1972, p. 401 and following) then use Eqn (14.6) to express C/C_o in terms of pore volumes p . However, the derivation involves calculus (the use of an error function), so we will not derive the equation. The advanced mathematical reader is referred to this derivation. For those without knowledge of calculus, a method is needed to calculate pore volumes.

14.4 CALCULATION OF A PORE VOLUME

To learn how to calculate pore volumes, let us use an example from the experiment by Vogeler et al. (2001). They studied phytoremediation of soil contaminated with copper using poplar. The lysimeter with the poplar is shown on the cover of the book edited by Iskandar and Kirkham (2001). A solution of copper in the form of $\text{Cu}(\text{NO}_3)_2$ was added to the surface of the soil (Manawatu fine sandy loam) in the lysimeter. Then, every day, the

lysimeter was irrigated and drainage water was collected. After running the experiment for 1 week, [Vogeler et al. \(2001\)](#) wanted to know how many pore volumes had passed through the lysimeter. One pore volume was calculated as follows. The shape of the lysimeter was that of a large cylinder, 1.30 m long with a diameter of 0.85 m. The volume of the lysimeter was

$$\begin{aligned}\text{volume} &= \pi r^2 h \\ \text{volume} &= \pi (0.85/2)^2 1.30 = 0.737 \text{ m}^3.\end{aligned}$$

Let θ_s = saturated water content = $0.40 \text{ m}^3/\text{m}^3$. This value was known from previous measurements.

$$\text{One pore volume} = \text{volume} \times \theta_s = 0.737 \text{ m}^3 \times 0.40 \text{ m}^3/\text{m}^3 = 0.295 \text{ m}^3.$$

$$0.295 \text{ m}^3 \times (1 \times 10^6 \text{ cm}^3)/(1 \text{ m}^3) = 295,000 \text{ cm}^3 = 295 \text{ liters}.$$

After 7 days of drainage, 70 L had been collected. Thus, $(70 \text{ L})/(295 \text{ L}) = 0.24$ or about $1/4$ pore volume.

To get one pore volume, [Vogeler et al. \(2001\)](#) needed to collect drainage water for 1 month. The experiment was run for 2 months to get two pore volumes.

Another example of calculating pore volumes is given by [Singh and Kanwar \(1991\)](#). They did a column study and calculated the value of one pore volume for each column by multiplying total porosity by the total volume of the soil column. Soil porosity for each column was estimated by using bulk density and particle density (Eqn 7.2). Note that in either case (the experiment by [Vogeler et al. \(2001\)](#) or the experiment by [Singh and Kanwar \(1991\)](#)), the whole pore volume is used to calculate pore volume. [Vogeler et al. \(2001\)](#) used the saturated water content (all pores filled with water); Singh and Kanwar used the total porosity.

In the theoretical development of pore volume ([Section 14.3](#)), the water-filled porosity, α , is used to calculate a pore volume. In practice, we do not know which pores have air and which pores have water, and hence, which pores are carrying the solute. So in our calculations in this section (above), the water-filled porosity becomes the porosity or the saturated water content. However, we note that the level of saturation affects the shape of the breakthrough curve. We see this by comparing [Figure 14.7](#), the breakthrough curve for a saturated soil, with [Figure 14.8](#), the breakthrough curve for an unsaturated soil. As one pore volume is attained, the slope in [Figure 14.7](#) is steeper than in [Figure 14.8](#).

14.5 PORE VOLUMES BASED ON LENGTH UNITS

Jury et al. (1991, pp. 224–225) and Jury and Horton (2004, pp. 230–232) calculate pore volumes by multiplying the length of a column by the water content. They give the formula

$$d_{wb} = J_w t_b = J_w L / V = L\theta, \quad (14.7)$$

where d_{wb} is the drainage water (cm) evolved at the breakthrough time $d_{wb} = J_w t_b$, J_w is the soil water flux (cm/s), t_b is the breakthrough time (s), L is the length of the soil column (cm), and V is the solute velocity (cm/s) (Figures 14.12 and 14.13). (We will assume this velocity as the average pore velocity that Kirkham and Powers define; the definition is given in a preceding section.) Jury et al. (1991, p. 225) and Jury and Horton (2004, p. 232) say that the value $L\theta$ is the volume of water per unit area held in the wetted soil pores of the column during transport. For this reason, $d_{wb} = L\theta$ is called a pore volume, and it requires approximately one pore

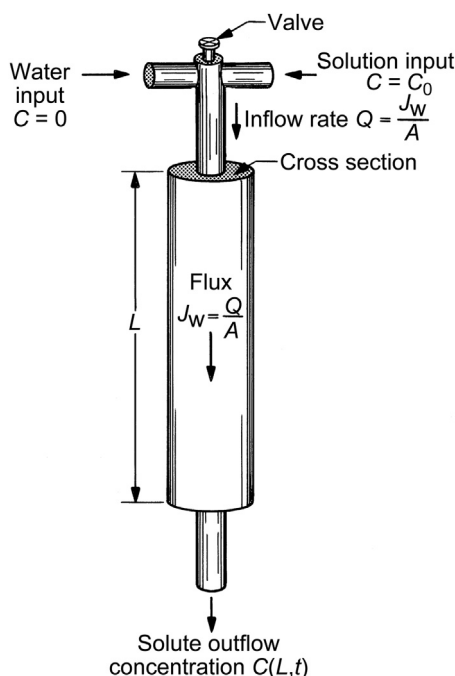


FIGURE 14.12 Schematic diagram of a soil column outflow experiment, where solute is added at $t = 0$. From Jury, W.A., Gardner, W.R., Gardner, W.H., *Soil Physics*, fifth ed., p. 224, ©1991, John Wiley & Sons: New York. This material is used by permission of John Wiley & Sons, Inc.

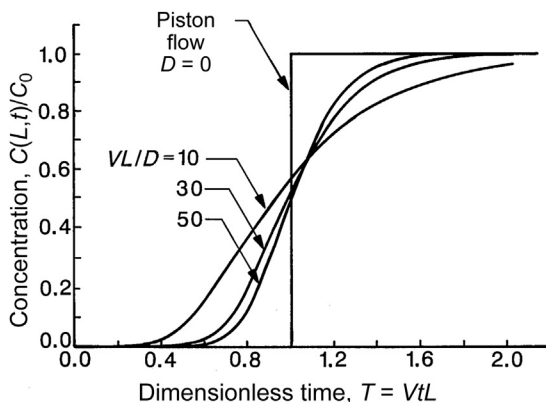


FIGURE 14.13 Outflow concentration versus time for a step change in solute input at $t = 0$. D = dispersion coefficient and it has units of $\text{length}^2/\text{time}$. If $D = 0$, there is no dispersion. Curves correspond to different values of D ($V = 2 \text{ cm/day}$, $L = 30 \text{ cm}$). From Jury, W.A., Gardner, W.R., Gardner, W.H., *Soil Physics*, fifth ed., p. 224, ©1991, John Wiley & Sons: New York. This material is used by permission of John Wiley & Sons, Inc.

volume of water to move a mobile solute through a soil column (Jury et al., 1991, p. 225; Jury and Horton, 2004, p. 232).

Why do Jury et al. (1991) and Jury and Horton (2004) use a length instead of a volume in getting a pore volume? A pore volume is a calculation of the equivalent amount of transmitted water in depth units (where the area has been taken out, as with evapotranspiration, where we use the units of millimeter). So in the case of Kirkham and Powers (1972), they deal with soil in which the water is being transmitted through the water-filled porosity. The calculation is turning the water that is being transmitted (i.e., a θ) into a volume, by multiplying by the soil's volume. But if one is dealing with areas, one can divide through by an area, as we do when we turn a (volumetric) water content (m^3/m^3) into a depth of storage water (mm) (B.E. Clothier, personal communication, February 25, 1999).

14.6 MISCIBLE DISPLACEMENT

Pore volumes are analyzed in miscible displacement studies. Miscible displacement is the process that occurs when one fluid mixes with and displaces another fluid. Leaching of salts from a soil is an example because the added water mixes with and displaces the soil solution. A pioneer in the application of miscible displacement techniques to soil science is D.R. Nielsen. (For a biography of Nielsen, see the Appendix, Section 14.8.) In a key paper, Nielsen et al. (1965) showed

that chloride movement in soil depends upon the method of water application. They found that intermittently ponding the soil with 2 in (5 cm) increments of water was more efficient in leaching applied chloride from the soil surface than continuous ponding or leaching with 6 in (15 cm) increments. This finding has important applications in salinity management.

For a mathematical discussion of miscible displacement, the interested reader is referred to [Kirkham and Powers \(1972\)](#), see their Chapter 8).

14.7 RELATION BETWEEN MOBILE WATER CONTENT AND PORE VOLUME

As noted in the first paragraph of this chapter, calculation of pore volumes does not tell us about the mobility of a solute, as we determined in Section 13.9, Chapter 13. The question arises, "How does one relate mobile water content to pore volumes?" Or, in other words, "How does the ratio of c^*/c_m , needed to determine mobility, relate to C/C_o on the ordinate in breakthrough curves?" The answer to this question is tricky. If we know that the soil wets to θ_o (the soil water content under a tension infiltrometer), then we can calculate the nonpreferential pore volume using this θ_o . But if our solute comes through earlier (i.e., a smaller pore volume), then not all the pore volume could have been active. So we could define an active pore volume, which we could directly relate to a mobile (volume) fraction, θ_m (B.E. Clothier, personal communication, February 25, 1999).

14.8 APPENDIX: BIOGRAPHY OF DONALD NIELSEN

Donald Rodney Nielsen, soil and water science educator, was born in Phoenix, Arizona, on October 10, 1931. He got his B.S. degree in agricultural chemistry and soils at the University of Arizona in 1953; his M.S. degree in soil microbiology at the University of Arizona in 1954; and his Ph.D. in soil physics at Iowa State University in 1958. His career has been spent at the University of California, Davis, where he started as an assistant professor in 1958, moved to associate professor in 1963, and then to professor in 1968. He became Professor Emeritus in 1994. He was the director of the Kearney Foundation of Soil Science from 1970 to 1975; associate dean, 1970–1980; director of the Food Protection and Toxicology Center, 1974–1975; chairman of the Department of Land, Air, and Water Resources, 1975–1977; executive associate dean of the College of Agricultural and Environmental Sciences, 1986–1989; and chairman of the Department of Agronomy and Range Science,

1989–1991 ([Marquis Who's Who, 1994](#)). In his administrative duties, he emphasized the important links between agriculture and environmental science.

Nielsen has been a pioneer in three areas of soil-science research: linking theory to field measurements of water movement, miscible displacement ([Nielsen and Biggar, 1962](#)), and geostatistics. One of his first papers with colleagues on geostatistics ([Nielsen et al., 1973](#)) became a citation classic ([Institute for Scientific Information, 1983](#)). He is the co-author of a book on soil hydrology ([Kutilek and Nielsen, 1994](#)) and a book on spatial and temporal statistics ([Nielsen and Wendroth, 2003](#)). He has edited several books, including a major compendium on nitrogen ([Nielsen and MacDonald, 1978](#)).

Nielsen has had an outstanding career not only in research and administration but also in teaching and serving as editor on important journals. Nielsen was an associate editor of *Water Resources Research* from when it was established in 1965 until 1986, and he was its editor-in-chief from 1986 to 1989. He has taught 15 different courses dealing with soil physics, water science, and irrigation. He has guided 17 students through to the M.S. degree and 20 students through to the Ph.D., and they are leaders in the field now. Seventy-five scientists from around the world have spent leaves with him.

He has taught workshops at numerous locations around the world, including the International Atomic Energy Agency in Vienna, Austria, and the famous International Center for Theoretical Physics, established by the Nobel Prize-winning Pakistani physicist, Abdus Salam, in Trieste, Italy.

Nielsen has won many awards. He is the Fellow of the American Society of Agronomy, the Soil Science Society of America, and the American Geophysical Union. He has been the president of the Soil Science Society of America, the American Society of Agronomy, and the Hydrology Section of the American Geophysical Union. He was on the National Research Council's Board on Agriculture. He received an honorary doctor of science degree from Ghent State University in Belgium and received the M. King Hubbert Award of the National Ground Water Association. He was made an honorary member of the European Geophysical Society and an honorary member of the Romanian Academy of Sciences. In 2001, he received the Horton Medal from the American Geophysical Union for outstanding contributions to the geophysical aspects of hydrology.

Nielsen maintains an active professional program and dedicates his time in educating soil physicists and hydrologists by daily answering their questions via e-mail. He collaborates with Miroslav Kutilek in writing about soils and climate ([Kutilek and Nielsen, 2010, 2013](#)). He married Joanne Joyce Locke on September 26, 1953. They have three daughters and two sons.

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