3 Soil Physics

For some, it is difficult to appreciate the discipline of soil science (Fig. 3.1). It sounds boring and like the word that soil scientists hate to hear: dirt. However, soil is a living ecosystem with nutrients, water, air, and microorganisms. It is the anchor for the roots and allows the plant to stand upright. The earth did not always have soil. There was only rock. In combination with chemical and physical weathering processes, plant roots built the soil. Early plants extended roots into rocks, and thus split apart the rocks into soil particles. Soils form slowly, which is why soil conservation is such an important concept.

Understanding the soil is the first key to successful irrigation and drainage system design. Infiltration rate is controlled by soil texture and structure. The water holding capacity and root depth determine the length of time between irrigation events. Matric potential becomes more negative as the soil dries. The matric potential level determines the ease with which plants remove water from the soil. When the soil dries beyond the management allowable depletion (MAD), the matric potential becomes too negative, and the plant uptake lags behind the crop water demand. One way to prevent excessive soil moisture depletion is to monitor the soil with soil moisture sensors. The soil moisture depletion can also be calculated based on the field capacity, permanent wilting point, and rate of evapotranspiration. The following soil parameters are reviewed in this chapter: soil layering, soil texture and structure, root zone depth, soil water holding capacity, and infiltration rate.

Soil Development and Layering

Layers (soil horizons) form in the soil with different structures and textures. Understanding the response of soil layers to irrigation and agricultural practices is essential to maintaining a productive soil environment. In saturated soils, tractors and overlying soil can cause the formation of plow layers, also known as hardpan. Plow layers restrict infiltration and root growth. Even sand layers can restrict infiltration. If a fine-textured soil layer is underlain by a sand layer, then water may remain perched above the sand because the capillary suction of the fine soil prevents the downward movement of water into the sand, which has very little capillary suction. Soil layering is also an important consideration for subsurface drainage systems design. If possible, drains should be placed in layers with high hydraulic conductivity.

Soil Texture

Soil particles are classified based on particle diameter. There are three major categories of soil particle size: sand, silt, and clay. The USDA particle size classification scheme is in Table 3.1.

Coarse sand has approximately the same diameter as pencil lead (Fig. 3.2) while the largest clay particle diameters are three orders of magnitude smaller. Based on the percentages of sand, silt, and clay, soils are classified by "textural class names" such as sandy loam, clay, and silt loam.

The USDA soil textural triangle is used to classify soil textures (Fig. 3.3).

In-class Exercise 3.1 Find the textural class name of soil with 40 % clay, 20 % sand, and 40 % silt?

Soil textures can also be classified (NRCS-NEH Part 652-2) based on the way that the soil responds in the hand (the feel and appearance method).

Sand—Sand is loose and single-grained. The individual grains can be readily seen and felt. Squeezed in the hand when dry, sand falls apart when pressure is released. Squeezed when moist, it forms a cast, but crumbles when touched.

Sandy loam—A sandy loam is soil containing a high percentage of sand, but having enough silt and clay to make it somewhat coherent. The individual sand grains can be readily seen and felt. Squeezed when dry, a sandy loam forms a cast that falls apart readily. If squeezed when moist, a cast can be formed that bears careful handling without breaking.

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Fig. 3.1 Soil scientist describing soil layers and roots (Credit Jeff Vanuga, NRCS)

Table 3.1 Particle size classification by USDA

Material	Diameter
Stones	>250 mm
Cobbles	80–250 mm
Course gravel	12.5–80 mm
Fine gravel	2.0–12.5 mm
Very coarse sand	1.0–2.0 mm
Coarse sand	0.5–1.0 mm
Medium sand	0.25–0.5 mm
Fine sand	0.1–0.25 mm
Very fine sand	0.05–0.1 mm
Silt	0.002–0.05 mm
Clay	Less than 0.002 mm

Loam—A loam is soil having a relatively even mixture of different grades of sand, silt, and clay. It is friable with a somewhat gritty feel, but is fairly smooth and slightly plastic. Squeezed when dry, it forms a cast that bears careful handling, and the cast formed by squeezing the moist soil can be handled freely without breaking.

Silt loam—A silt loam is soil having a moderate amount of fine sand with a small amount of clay. Over half of the particles are silt size particles. When dry, a silt loam appears cloddy, but the lumps can be readily broken. When pulverized, it feels soft and floury. When wet, the soil runs together readily and puddles. Either dry or moist, silt loam forms a cast that can be handled freely without breaking. When moist and squeezed between thumb and finger, it does not ribbon, but has a broken appearance.

Clay loam—A clay loam is moderately fine-textured soil that generally breaks into clods or lumps that are hard when dry. When the moist soil is pinched between the thumb and finger, it forms a thin ribbon that breaks readily, barely sustaining its own weight. The moist soil is plastic and forms a cast that bears much handling. When kneaded in the hand, clay loam does not crumble readily, but works into a heavy compact mass.

Clay—A clay is fine-textured soil that usually forms very hard lumps or clods when dry and is very sticky and plastic when wet. When moist soil is pinched between thumb and finger, it forms a long flexible ribbon. Some clays are very high in colloids are friable and lack plasticity.

Three laboratory methods are commonly used to measure soil particle size distribution: laser particle size analysis, hydrometer and sieve. The state of the art is the laser system, which can measure hundreds of samples per day. The traditional method for measuring small particle size is the hydrometer, which measures the rate that particles sink in quiescent water. This method is based on Stoke's law of falling bodies. It requires manual observation and can only measure one sample per day. A series of standard sieves can be used to measure larger particles with diameters greater than 2 microns (coarse sand and larger).

Once the soil texture is known, the Soil Water Characteristics Calculator (URL in References) calculates soil hydraulic properties. The Calculator also includes compaction, which incorporates the soil structure concepts described below.

Soil Structure

Soil structure has a strong influence on soil properties. Soil structure is defined by the NRCS as follows:

> Soil structure is the arrangement and organization of soil particles into natural units of aggregation. These units are separated from one another by weakness planes that persist through cycles of wetting and drying and cycles of freezing and thawing. Structure influences air and water movement, root development, and nutrient supply.

Soil structure strongly influences infiltration rate. Single grain soils are sands with no cementing agents attaching particles to each other. Granular soils are aggregates of small particles. Both of these soils have rapid infiltration rates. Blocky and prismatic soils are larger aggregates and have moderate infiltration rates. Although platy structures are aggregates, they have poor vertical infiltration. Massive

Fig. 3.2 Soil particle sizes (Courtesy of Don Post. The University of Arizona)

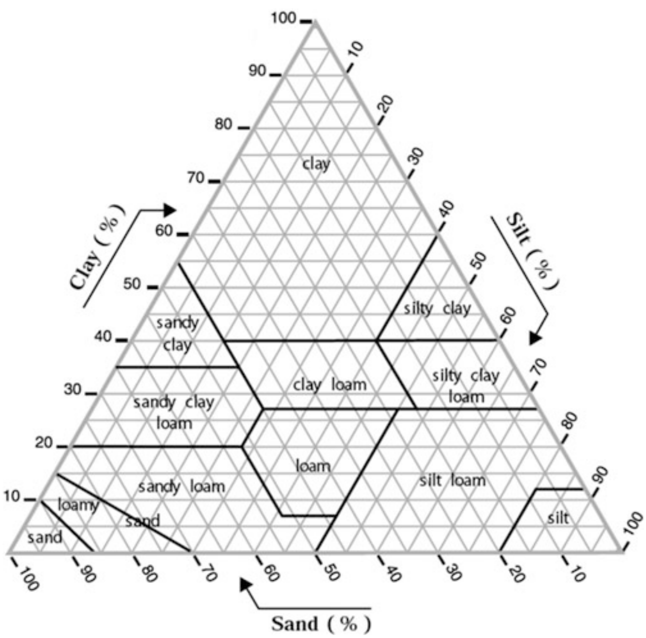

Fig. 3.3 USDA soil textural triangle (Credit NRCS, National Agronomy Manual. Part 504)

soils are generally grossly swelling soils (montmorrilonite clay). These soils have extremely low infiltration rates.

Cultural practices can either improve (increase porosity and hydraulic conductivity) or degrade soil texture (increase density). For example, driving a tractor in a wet field can decrease soil structure and form hardened layers with low infiltration rates.

Root Zone

The depths to which roots of various mature crops will extract available water are shown in Table 3.2. The reported depths in Table 3.2 are 80 % of actual root zone depths because plants extract most of their water from the upper portion of the root zone.

A rule of thumb that is applied to root water uptake is that 40 % of plant water uptake is from the upper 25 % of the root zone, 30 % from the next, 20 % from the next, and 10 % from the lowest quarter of the root zone (Fig. 3.4).

Soil-Water Relationships

The two most important parameters that describe the status of water in soil are water content and total water potential. Water content refers to the fraction of the soil that is occupied by water and can be measured by mass or volume. Total water potential refers to the energy of the water in soil and generally includes matric potential (also called capillary potential or moisture potential), gravitational potential due to elevation, and osmotic potential due to salinity.

Water content can be calculated gravimetrically or volumetrically. Gravimetric soil water content is the mass of water divided by the mass of dry soil. It can be measured by weighing a mass of wet soil, drying the soil for 24 hours at 105 °C, and then reweighing the sample.

$$\theta_{grav} = \frac{m_{water}}{m_{dry\ \ soil}} = \frac{m_{wet\ \ soil} - m_{dry\ \ soil}}{m_{dry\ \ soil}} \qquad (3.1)$$

where

θ_{grav} = gravimetric water content, gm/gm
m_{water} = mass of water, gm.
$m_{dry\ soil}$ = mass of soil after drying, gm.
$m_{wet\ soil}$ = mass of soil before drying, gm.

Example 3.1 A soil sample is collected just before irrigation, and another soil sample is collected two days after irrigation. The soil sample collected before irrigation weighs 1.73 kg, and the soil collected just after irrigation weights 1.94 kg. Both soils are placed in an oven and dried at 100 °C

Table 3.2 Depth to which roots of mature crops will extract available water from a deep uniform, well-drained soil under average unrestricted conditions (depths shown are 80 % of the entire root zone depth). (Credit NRCS NAM 504-4)

Crop	Depth (m)	Crop	Depth (m)
Alfalfa	1.5	Milo	0.6–1.2
Asparagus	1.5	Mustard	0.6
Bananas	1.5	Onions	0.3–0.6
Beans, dry	0.6–0.9	Parsnips	0.6–0.9
Beans, green	0.6–0.9	Peanuts	0.6–0.9
Beets, table	0.6–0.9	Peas	0.6–0.9
Broccoli	0.6	Peppers	0.3–0.6
Berries, blue	1.2–1.5	Potatoes, Irish	0.6–0.9
Berries, cane	1.2–1.5	Potatoes, sweet	0.6–0.9
Brussels sprouts	0.6	Pumpkins	0.9–1.2
Cabbage	0.6	Radishes	0.3
Cantaloupes	0.9	Safflower	1.2
Carrots	0.6	Sorghum	1.2
Cauliflower	0.6	Spinach	0.3–0.6
Celery	0.3–0.6	Squash	0.9–1.2
Chard	0.3–0.6	Strawberries	0.3–0.6
Clover, Ladino	0.6–0.9	Sudan grass	0.9–1.2
Cranberries	0.3	Sugar beets	1.2–1.5
Corn, sweet	0.6–0.9	Sugarcane	1.2–1.5
Corn, grain	0.9–1.2	Sunflower	1.2–1.5
Corn, seed	0.9–1.2	Tobacco	0.9–1.2
Corn, silage	0.9–1.2	Tomato	0.9
Cotton	1.2–1.5	Turnips	0.6– 0.9
Cucumber	0.3–0.6	Watermelon	0.9– 1.2
Eggplant	0.6	Wheat	1.2
Garlic	0.3–0.6	Trees	
Grains and flax	0.9–1.2	Fruit	1.2–1.5
Grapes	1.5	Citrus	0.9–1.2
Grass pasture/hay	0.6–1.2	Nut	1.2–1.5
Grass seed	0.9–1.2		
Lettuce	0.3–0.6		
Melon	0.6–0.9		

for 24 hours. After drying, the soil collected just before irrigation weighs 1.49 kg and the soil collected just after irrigation weighs 1.52 kg. What are the volumetric water contents just before and just after irrigation?

Solution:
Gravimetric water content just before irrigation

$$\theta_{grav} = \frac{1.79\ \ kg - 1.49\ \ kg}{1.49\ \ kg} = 0.20 = 20\%$$

Gravimetric water content just after irrigation

$$\theta_{grav} = \frac{1.94\ \ kg - 1.52\ \ kg}{1.52\ \ kg} = 0.27 = 27\%$$

Water content collected two days after irrigation is close to field capacity because the soil has drained, but there has been little evaporation after drainage.

Gravimetric water content soil samples can be collected with a shovel or auger because the measurement is not dependent on the volume of soil. Volumetric water content is defined as the percent of total soil volume that is occupied by water and is more difficult to measure than gravimetric water content because it is based on soil volume. Gravimetric water content is converted to volumetric water content by multiplying by the soil bulk density.

$$\theta_v = \theta_{grav}\rho_b = \theta_{grav}\frac{\rho_b}{1} = \theta_{grav}\frac{\rho_b}{\rho_w} = \theta_{grav}\ \ \rho_b \tag{3.2}$$

where

θ_v = volumetric water content, cm^3/cm^3
ρ_b = soil bulk density, gm/cm^3.
ρ_w = density of water, 1 gm/cm^3.

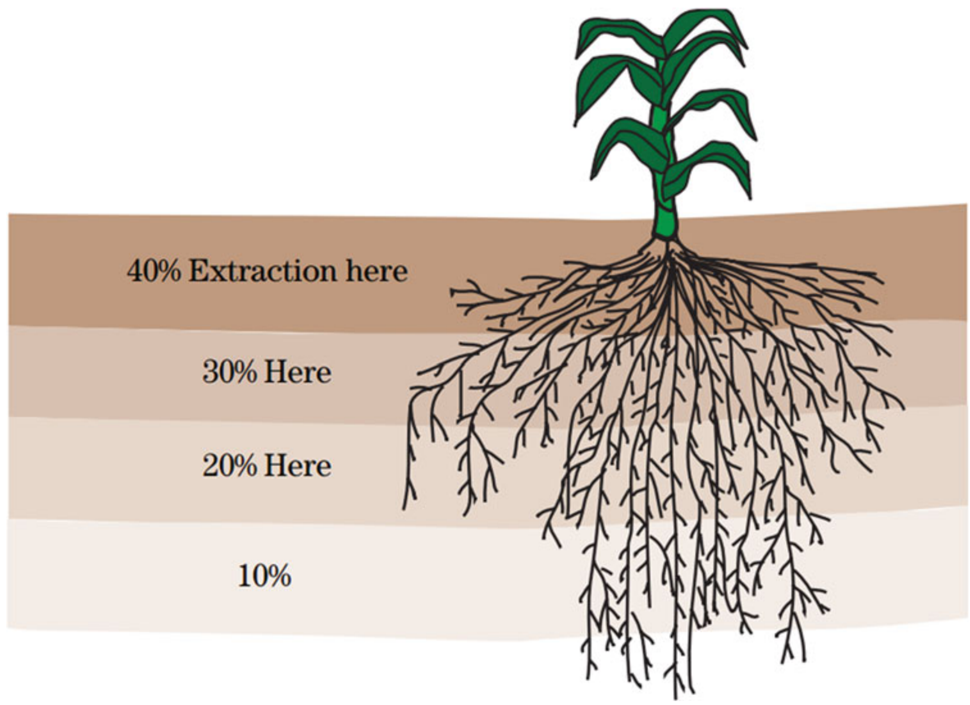

Fig. 3.4 Typical water uptake pattern (Credit: NRCS)

The soil bulk density (ρ_b) is the mass of dry soil divided by the volume of soil. Specialized soil sampling tools are used for collection of undisturbed soils for measurement of bulk density – the soil sample must be collected in a cylinder of known size, and the soil sample within the cylinder must be undisturbed. One such device is a bucket auger (cylinder), with slots at the top and bottom of the cylinder. Knives are inserted into the slots, and soil is removed above and below the sample. Then the knives are removed and the soil is pushed out of the auger into a drying can, which is then dried in the oven. A second type of bulk density sampling device is a small metal cylinder that is inserted into the soil and removed with the soil sample. Excess soil is then scraped off above and below the cylinder.

Soil bulk density can range from 1 to 2 g/cm^3. Typical clay, loam, and sandy soils have bulk densities equal to 1.3-, 1.5-, and 1.8-g/cm^3, respectively. Organic matter or fossilized shells can cause the bulk density to even be less than 1 g/cm^3, the density of water.

Porosity is the fraction of voids in a soil (air + water). It can be calculated based on the bulk density of a soil and the average particle density of soil particles. Average particle density of mineral soils is 2.65 g/m^3.

$$\phi = 100 - \left(\frac{\rho_b}{\rho_p}\right)(100) \tag{3.3}$$

where

ϕ = porosity (fraction of voids), percent
ρ_p = particle density, 2.65 g/cm^3 for mineral soils.

Example 3.2 The soils described in Example 3.1 have bulk density 1.3 g/cm^3. Find the volumetric water contents and porosity of the two samples.

Solution:
Volumetric water content just before irrigation

$$\theta_v = \theta_{grav}\rho_b = (0.20\ \ g/g)\left(1.3\ \ g/cm^3\right) = 0.26 = 26\%$$

Volumetric water content just after irrigation

$$\theta_v = \theta_{grav}\rho_b = (0.27\ \ g/g)\left(1.3\ \ g/cm^3\right) = 0.36 = 36\%$$

The bulk density is 1.3 g/cm^3 and soil particle density is 2.65 g/cm^3.

$$\phi = 100 - \left(\frac{1.3}{2.65}\right)(100) = 51\%$$

This means that 51 % of the soil volume is filled with air or water.

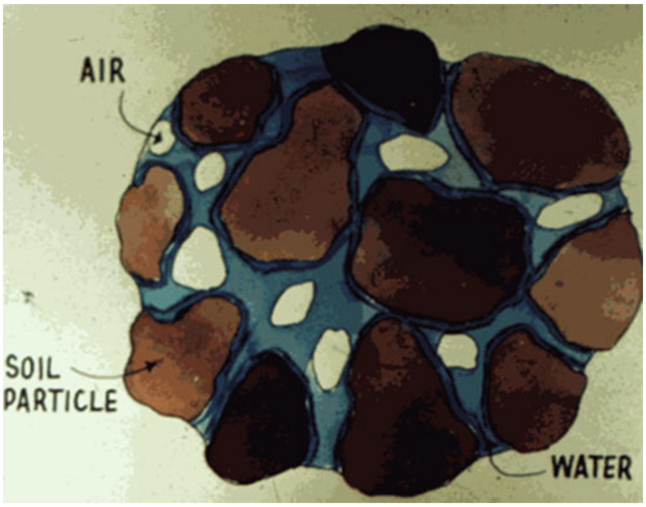

Fig. 3.5 Field capacity (Courtesy of Don Post. The University of Arizona)

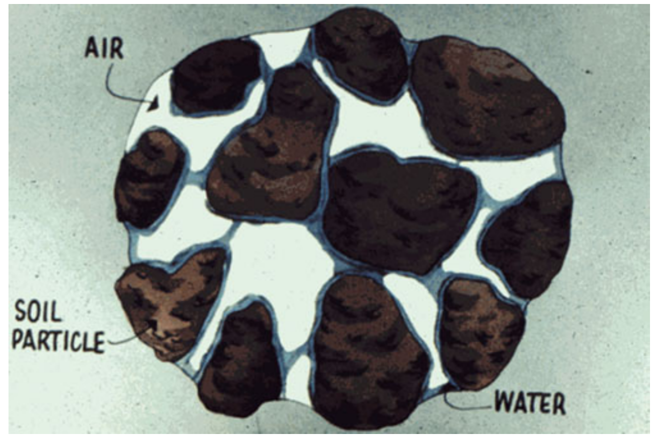

Fig. 3.6 Permanent wilting point (Courtesy of Don Post. The University of Arizona)

Three primary water content percentages are generally considered in irrigation and drainage system designs: saturation (θ_{sat}), field capacity (θ_{FC}), and permanent wilting point (θ_{PWP}).

Saturated soils have nearly all pore space filled by liquid, except for a small percentage of pores with trapped air: thus, saturated water content is approximately equal to porosity. High water content is not desirable because it restricts oxygen diffusion from the atmosphere into the soil because most of the soil pores are occupied by water: oxygen diffusion is approximately 1,000 times greater in a gas than it is in water. This lack of oxygen restricts oxygen uptake by plant roots during respiration.

Field capacity (Fig. 3.5) is the amount of water left in the soil after free drainage by gravity (larger soil pores are drained by gravity). This takes place quickly in coarse textured soils (a few hours), less quickly in medium textured soils (24 hr) and slowly (several days) in fine textured soils.

Field capacity can be estimated in the laboratory by applying a vacuum. A suction of – 0.01 MPa (−0.1 atm) is applied to sandy soils and a suction of – 0.03 MPa (−0.3 atm) is applied to clay soils. Then, the soil is weighed, dried, and then reweighed in order to calculate gravimetric water content at field capacity. Volumetric water content at field capacity can be calculated if porosity and bulk density of the soil are known.

The wilting point (Fig. 3.6) is the water content at which a crop cannot remove water from the soil quickly enough to prevent wilting and tissue damage. This point varies for different crops and varies with evapotranspiration demand because the process of water moving to the root is time dependent. Permanent wilting point (PWP) is generally defined as a soil water potential equal to −1.5 MPa (−15 atm). In the laboratory, permanent wilting point is measured by placing the soil in a cylinder on a porous plate, applying a positive pressure of 1.5 MPa (15 atm), and pushing the water from the soil through the porous plate.

Theoretical field capacities and permanent wilting points for various soils can be calculated with the Soil Water Characteristics Calculator.

The total energy of water in soils is generally negative due to capillary suction. It becomes more negative when the soils have high salinity because the salts hold the water by osmotic potential. Thus, saline soils have less water available to the plant than nonsaline soils.

Chemical (osmotic), elevation (gravitation), and matric (hydraulic) potential energy are all components of the total energy of water in soils, H. Thermal energy can also influence the direction of water flow, although it is not included in soil water calculations in this text. Water velocity is extremely slow in soils so kinetic energy is not a significant component of water energy in soils. Thus, the total potential of water in soils is expressed as follows:

$$H = \frac{P}{\rho g} + z + \psi_s = \psi_p + z + \psi_s \qquad (3.4)$$

where

ψ_s = osmotic potential, m
ψ_p = capillary or hydraulic (pressure) potential (also equal to h_c in Eq. 3.4), m
z = elevation, m
P = pressure, N/m^2
ρ = density of water, kg/m^3
g = gravity, 9.8 m/sec^2

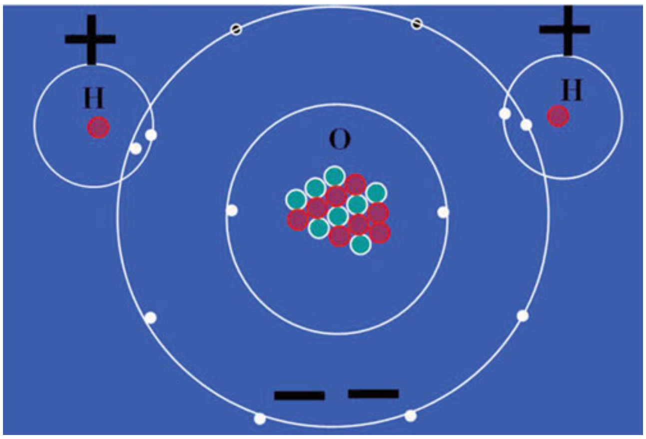

Fig. 3.7 Water molecule

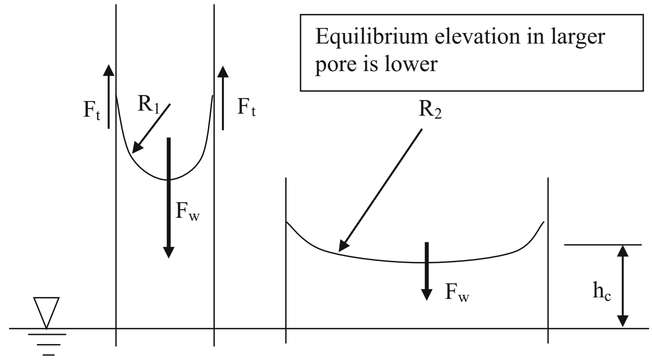

Fig. 3.8 Capillary force (matric potential)

Water molecules are attracted to each other because the negative side of one water molecule (Fig. 3.7) is attracted to the positive side of another. This force of attraction due to polarity of the water molecule has several names: hydrogen bonds, Van der Waal's force, or electrostatic attraction. In the liquid state, water demonstrates cohesion up to a suction of approximately 30 MPa or 30,000 kPa (300 atmospheres). Water cohesion is an important water property in soils and plants since water must flow from the soil to the plant root and then upward in the plant at extremely negative water potentials. Cohesion also causes water to form a meniscus under negative pressure due to water surface tension. If the radius of the meniscus in a pore is small, then the force, $-F_\tau$, is large, and it is very difficult to remove water from the pore; thus, the energy of the water can be much more negative in small pores.

The energy in hydrogen bonds between water molecules is approximately 20 kJ/mole of water;

$$\left(\frac{20\ kJ}{mole}\right)\left(\frac{mole}{18\ g}\right)\left(\frac{1{,}000\ g}{kg}\right) = 1{,}100\ kJ/kg$$

The energy required to evaporate water, the latent heat of vaporization, is 2,450 kJ/kg. Thus, significant part of the energy used to evaporate water is used to break hydrogen bonds.

The downward force on the meniscus in Fig. 3.8 is gravity.

The equation that determines the negative hydraulic pressure (capillary potential) exerted by a meniscus is based on the law of conservation of momentum: summation of forces equals zero.

$$F_\tau = -F_w \quad 2\pi R\tau = -\rho g h_c \pi R^2 \quad \psi_p = h_c = -\frac{2\tau}{\rho g R} \tag{3.5}$$

where

F_τ = upward force of clay surface on water, N
F_w = downward force of water column, N
h_c = matric potential, m
τ = surface tension of water, 0.073 N/m = 73 dyne/cm
R = pore radius, m.

Matric (capillary) potential energy is commonly expressed in atmospheres (also called bars). Air density at sea level is 1.23 kg/m^3 or 101.3 kPa (1 atmosphere). Units of pressure (kPa) are converted to units of length by dividing by the specific weight (ρg) of water.

$$\frac{P}{\rho g} = \frac{1.013{*}10^5\ Pa}{1{,}000\ kg/m^3{*}9.801\ m/\sec^2} = 10.34\ m \tag{3.6}$$

Example 3.3 Calculate the matric potential at which pores begin to drain in clay soils (R = 1 *10^{-6} m) and fine sand soils (R = 50 microns).

Clay
$$h_c = -\frac{2\tau}{\rho g R} = \frac{-2{*}0.073}{1{,}000{*}9.8{*}10^{-6}} = -15\ m{*}\left(\frac{atm}{10.34\ m}\right) = -1.45\ atm$$

Sand
$$h_c = \frac{-2{*}0.073}{1{,}000{*}9.8{*}0.00005} = -0.3\ m{*}\left(\frac{atm}{10.34\ m}\right) = -0.03\ atm$$

Water is strongly attracted to negatively charged clay surfaces. This attraction to other materials is called adhesion. The closer water molecules are to clay surfaces, the more negative is their potential energy and the more difficult it is to remove them from the soil.

The energy of water in air is even more negative than energy of water in soils. Thus, water flows from the relatively higher energy in the soil to the lower energy in the atmosphere. The plant acts as a passive conduit for the water as it flows from the soil to the atmosphere. The plant maintains positive hydraulic pressure during this process by having negative osmotic potential due to high sugar concentration in cells.

The relationship between matric potential (moisture potential) and water content for typical soils is shown in Fig. 3.9. The moisture potential axis has a log scale: moisture potential drops by 2 orders of magnitude in Fig. 3.9 between saturation and field capacity and then between field capacity and permanent wilting point.

In general, soil water content should remain above the 30 % depletion line (MAD = 30 %) for drought sensitive crops and above 50 % depletion for drought tolerant crops in order to avoid yield reduction.

The water content – moisture potential relationship varies dramatically between soils. Soils with medium texture have the most water availability. Clay soils have a large fraction of small, flat pores, and much of the water in clays is unavailable to the plant because plants cannot develop a negative enough osmotic potential to extract water from small pores. One the other hand, large pores in sand drain quickly after rainfall before plants can utilize the water.

The difference between field capacity and permanent wilting point is called available water capacity. AWC is the fraction of soil volume between field capacity and permanent wilting point.

$$\mathrm{AWC} = \theta_{\mathrm{FC}} - \theta_{\mathrm{PWP}} \tag{3.7}$$

where

AWC = available water capacity, fraction or percent.

The soil water holding capacity (SWHC) is the depth of water in the soil available for plant growth. SWHC is also known as total available water (TAW)

$$\mathrm{SWHC} = \mathrm{TAW} = (\mathrm{AWC})(z) \tag{3.8}$$

where

SWHC or TAW = soil water holding capacity or total available water, m
z = root zone depth, m

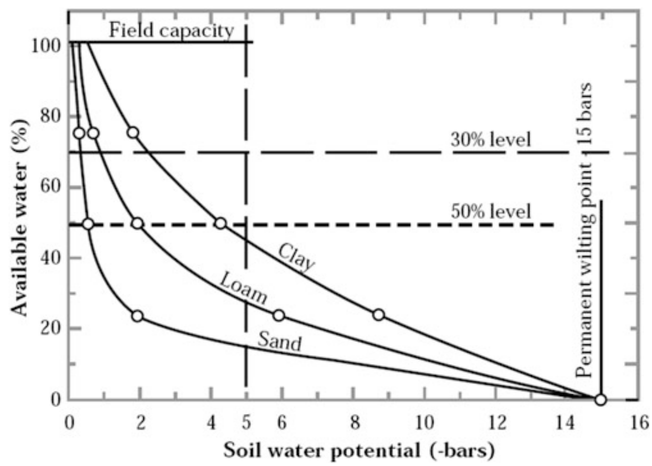

Fig. 3.9 Depletion percentages for different soils versus soil water potential (Credit NRCS)

Example 3.4 The root depth of an orange tree is 1.5 m. The soil has 56 % solid particles, and 44 % voids. After drainage, the 50 % of the void volume contains water and 50 % holds air. At the wilting point, the void volume is 25 % water. What is the soil water holding capacity (SWHC).

Solution:

$$\begin{aligned}
&\text{Field capacity} = (0.44)\ (0.5) = 0.22 = 22\% \\
&\text{Permanent wilting point} = (0.44)\ (0.25) = 0.11 = 11\% \\
&\mathrm{AWC} = \theta_{\mathrm{FC}} - \theta_{\mathrm{PWP}} = 0.22 - 0.11 = 0.11 \\
&\mathrm{TAW} = \mathrm{SWHC} = (\mathrm{AWC})(z) = 0.11(1.5\ \mathrm{m}) \\
&\qquad = 0.165\ \mathrm{m} = 16.5\,\mathrm{cm}.
\end{aligned}$$

Note: Only about half of the SWHC or TAW (total available water) is available to the plant so only about 8 cm of water would be available between irrigation events. This means that if the evapotranspiration rate was 1 cm/day, then the field would need to be irrigated every 8 days.

Depletion is the depth of water removed from the soil (after the soil reaches field capacity by gravity drainage) by evapotranspiration. Percent depletion is percent of the TAW that is removed by evapotranspiration. Percent depletion is 0 % at field capacity and 100 % at permanent wilting point. Depletion and percent depletion are calculated as follows.

$$\begin{aligned}
&\text{Depletion} = \mathrm{D_r} = (\theta_{\mathrm{FC}} - \theta)z \\
&\%Dep = \frac{D_r}{TAW}*100 = \frac{(\theta_{FC} - \theta)}{(\theta_{FC} - \theta_{PWP})}(100)
\end{aligned} \tag{3.9}$$

Example 3.5 The soil described in Example 3.2 has a permanent wilting point equal to 20 % (volumetric water content). Calculate the percent depletion in the soil sample in Example 3.2 taken just before irrigation. If the root zone is 1 m deep, then what is the depth of depletion?

Solution:

Find the percent depletion

$$\%Dep = \frac{(\theta_{FC} - \theta)}{(\theta_{FC} - \theta_{PWP})}(100) = \frac{(0.36 - 0.26)}{(0.36 - 0.2)}(100)$$
$$= 63\%$$

Find the total available water in order to find the depth of depletion.

$$\begin{aligned} AWC &= \theta_{FC} - \theta_{PWP} = 0.36 - 0.2 = 0.16 \\ TAW &= SWHC = (AWC)(z) = 0.16\ (1\ \text{m}) \\ &= 0.16\ \text{m} = 16\ \text{cm} \end{aligned}$$

Find the depth of depletion

$$\frac{\%Dep}{100}TAW = D_r = \frac{63}{100}(16\ \ cm) = 10\ \ cm$$

The percent depletion with no yield reduction for specific crops is called the management allowed depletion (MAD). The MAD value for many crops changes with growth stage (Table 3.3) and is based on the crop sensitivity to water stress at that stage. The MAD value for a drought tolerant crop is approximately 0.5 and the MAD value for a drought sensitive crop is approximately 0.2.

The readily available water (RAW) is the depth of water available to the plant between irrigation events.

$$RAW = (TAW)(MAD) \tag{3.10}$$

where
MAD = management allowed depletion, fraction
RAW = readily available water, m.

Example 3.6 Use the soil described in Example 3.5. A crop has an MAD value of 0.4 and a root zone depth of 1 m. What is the RAW? The depth of evapotranspiration is 1 cm/day. How often would the field need to be irrigated?

Solution:

$$RAW = (TAW)(MAD) = (16\ \text{cm})(0.43) = 7\ \text{cm}.$$

Thus, if the evapotranspiration rate was 1 cm/day, then the field would need to be irrigated once per week.

In order to find the preferred volumetric water content at which the next irrigation should take place, subtract AWC (MAD) from the field capacity.

Example 3.7 Use the soil described in Example 3.5. Find the preferred water content at which irrigation should be take place for a plant with 40 % MAD.

Solution:

$$\begin{aligned} \text{Water content at next irrigation} &= FC - (AWC)(MAD) \\ &= FC - (FC - PWP)(MAD) \\ &= (0.36) - (0.36 - 0.20)(0.40) \\ &= 0.30 = 30\% \end{aligned}$$

Note: 30 % is a higher water content than the soil water content taken just before irrigation in Example 3.2. Thus, a plant with a 0.4 MAD would have been overly stressed before irrigation.

With infrequent irrigation, such as with orchard sprinkler systems or surface irrigation systems, irrigation should replace the RAW. Frequent irrigation with drip or center pivots keeps the soil moist and does not approach the MAD.

Table 3.3 Recommended Management Allowed Depletion (MAD) values for loamy soils (Credit NRCS)

	Establishment	Vegetative	Flowering	Ripening
Alfalfa hay	50	50	50	50
Alfalfa seed	50	60	50	80
Beans, green	40	40	40	40
Beans, dry	40	40	40	40
Citrus	50	50	50	50
Corn, grain	50	50	50	50
Corn, seed	50	50	50	50
Corn, sweet	50	40	40	40
Cotton	50	50	50	50
Cranberries	40	50	40	40
Garlic	30	30	30	30
Grains, small	50	50	40	60
Grapes	40	40	40	50
Grass pasture/hay	40	50	50	50
Grass seed	50	50	50	50
Lettuce	40	50	40	20
Milo	50	50	50	50
Mint	40	40	40	50
Nursery stock	50	50	50	50
Onions	40	30	30	30
Orchard, fruit	50	50	50	50
Peas	50	50	50	50
Peanuts	40	50	50	50
Potatoes	35	35	35	50[4/]
Safflower	50	50	50	50
Sorghum, grain	50	50	50	50
Spinach	25	25	25	25
Sugar beets	50	50	50	50
Sunflower	50	50	50	50
Vegetables				
30–60 cm root depth	35	30	30	35
90–120 cm root depth	35	40	40	40

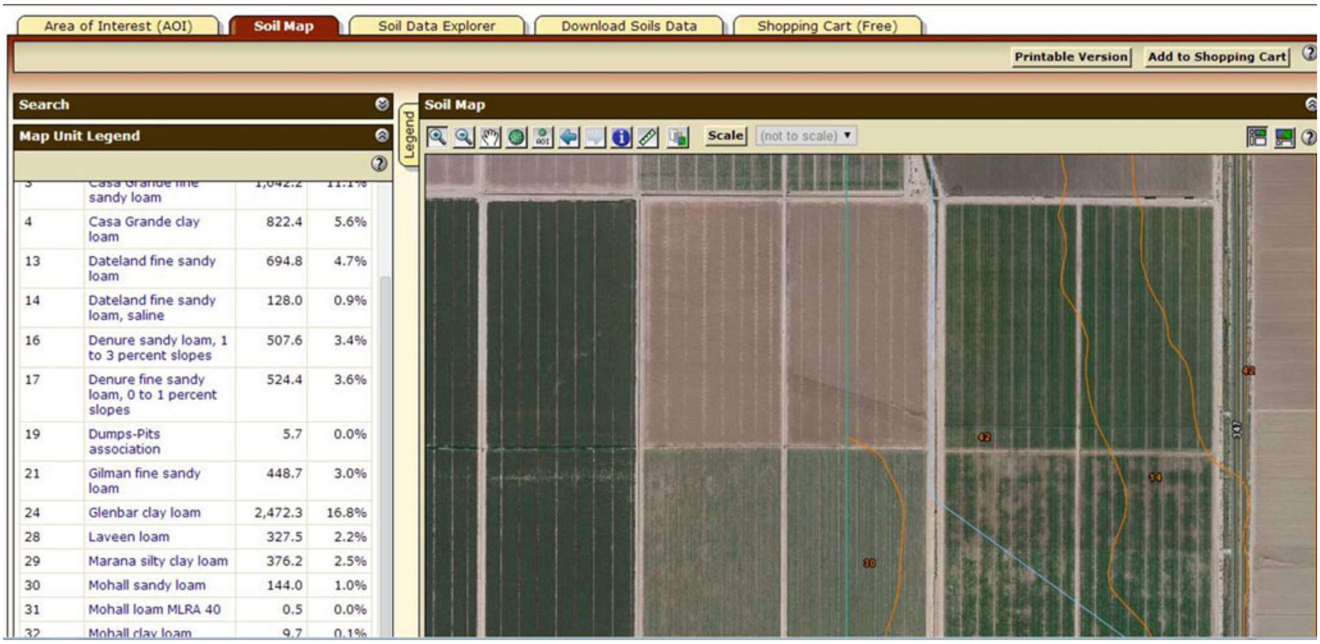

Fig. 3.10 Web soil survey map

Recommended MAD values from NRCS for loamy soils are shown in Table 3.3. A document called FAO56 (Allen et al. 1998) is a standard reference for evapotranspiration and plant stress and it presents a slightly different concept for MAD estimation: the crop stress threshold, p, is similar to the MAD but not the same. FAO 56 lists p values in its Table 22 and adjusts p values based on ETc as follows: $p = p_{\text{Table 22}} + 0.04\ (5 - ET_c)$. Thus, the p value decreases for high evapotranspiration. This is because plant water uptake is a time dependent process and if water is needed more quickly, then the soil water content should be higher. Soil texture also affects p. FAO56 recommends increasing p by 5–10 % in a coarse (sandy) textured soil and decreasing p by 5–10 % in a fine textured soil.

Many factors can change available water capacity. The available water capacity (AWC) is obviously reduced if the soil has rocks. Organic matter can decrease bulk density and increase porosity by up to 10 %. Good soil structure (granular, blocky, or prismatic) can increase AWC by 10 % whereas poor soil structure (massive, platy, or single grain) can decrease AWC by 10 %. Compaction can decrease AWC by 20 %. Restrictive layers can increase the AWC in the layers above by 10 % by restricting downward flow of water by gravity. Soils increase in density with depth because of over-burden pressure, decreased structure, and decreased organic matter. Thus, AWC decreases by approximately 5 % per 30 cm depth in the soil. Vegetation can increase AWC because roots improve soil structure and condition.

Characterization of Soil Layers

In layered soils, the SWHC for the soil profile is the sum of the products of the AWCs and the layer thicknesses

$$SWHC = \sum_{i=1}^{n} SWHC_i = \sum_{i=1}^{n} \Delta z_i * AWC_i \qquad (3.11)$$

where

Δz = thickness of soil layer, cm
i = soil layer number
n = number of layers.

In preparation for an irrigation or drainage design, soils analysis optimally includes drilling soil cores and digging soil pits in order to characterize soil. A less preferable, but less expensive, alternative is to use published soil map descriptions; for example, Web Soil Survey (websoilsurvey.sc.egov.usda.gov) is hosted by the United States Department of Agriculture (USDA). After defining an area of interest (AOI), you can click on the Soil Map tab to find the soils in the AOI (Fig. 3.10). Each of the numbered soil types in the Map Unit Legend on the left corresponds to a number in the soil map.

The soils listed in the Map Unit legend can be found at the Soil Series Description web site (https://soilseries.sc.egov.usda.gov/osdname.asp). For example, one of listed soils is

Mohall sandy loam (#30). Just type Mohall into the textbox at the Soil Series Description web site, and the following description appears. The sandy loam should not be typed into the textbox because it just refers to the upper layer of soil.

Mohall Series

The Mohall series consists of very deep, well-drained soils formed in fan and stream alluvium from mixed sources. Mohall soils are on fan terraces, stream terraces, and relict basin floors and have slopes of 0–8 %. The mean annual precipitation is about 6 inches and the mean annual air temperature is about 73°F.

TAXONOMIC CLASS: Fine-loamy, mixed, superactive, hyperthermic Typic Calciargids

TYPICAL PEDON: Mohall coarse sandy loam - rangeland. (Colors are for dry soil unless otherwise noted.)

A--0–4 inches; reddish yellow (7.5 YR 6/6) coarse sandy loam, brown (7.5 YR 4/4) moist; weak medium platy structure parting to weak fine granular; slightly hard, very friable, slightly sticky and slightly plastic; few fine roots; many very fine and fine irregular and common fine tubular pores; moderately alkaline (pH 7.9); abrupt wavy boundary. (2–7 inches thick)

BA--4–10 inches; strong brown (7.5 YR 5/6) coarse sandy loam, brown (7.5 YR 4/4) moist, weak coarse angular blocky structure parting to weak medium subangular blocky; slightly hard, very friable, slightly sticky and slightly plastic; common fine and very fine roots; common very fine and few fine tubular pores; few faint clay films on faces of peds and lining pores; moderately alkaline (pH 7.9); clear wavy boundary. (2–8 inches thick)

Bt--10–19 inches; brown (7.5 YR 5/4) sandy clay loam, reddish brown (5 YR 4/4) moist; moderate medium and coarse prismatic structure parting to moderate medium and coarse angular blocky; very hard, friable, very sticky and very plastic; few fine roots; few fine and very fine tubular pores; many faint clay films on faces of peds and lining pores; moderately alkaline (pH 8.0); clear wavy boundary. (5–10 inches thick)

Btk1--19–27 inches; brown (7.5 YR 5/4) clay loam, reddish brown (5 YR 4/4) moist; weak medium prismatic structure parting to moderate medium subangular blocky; very hard, friable, very sticky and very plastic; few very fine roots; common faint clay films on faces of peds; strongly effervescent as common fine calcium carbonate filaments and few small concretions; moderately alkaline (pH 8.2); clear wavy boundary. (6–12 inches thick)

Btk3--27–37 inches; strong brown (7.5 YR 5/6) loam, brown (7.5 YR 4/4) moist; weak fine and medium subangular blocky structure; slightly hard, very friable, moderately sticky and moderately plastic; few very fine roots; common very fine and fine tubular pores; few faint clay films on faces of peds and lining pores; strongly effervescent as common medium distinct calcium carbonate filaments and masses; moderately alkaline (pH 8.2); clear wavy boundary. (5–15 inches thick)

2Bk--37–54 inches; pinkish white (7.5 YR 8/2) gravelly sandy loam, pinkish gray (7.5 YR 7/2) moist; massive; hard, friable, slightly sticky and slightly plastic; common very fine and fine tubular pores; 20 % gravel; violently effervescent as common soft calcium carbonate masses; moderately alkaline (pH 8.0); gradual wavy boundary. (12–24 inches thick)

2C1--54–76 inches; pinkish white (7.5 YR 8/2) gravelly sandy loam, pink (7.5 YR 7/4) moist; massive; very hard, friable, nonsticky and nonplastic; common fine tubular pores; 25 % gravel; violently effervescent; moderately alkaline (pH 8.2); gradual wavy boundary. (20–30 inches thick)

2C3--76–98 inches; pinkish gray (7.5 YR 7/2) gravelly loamy coarse sand, light brown (7.5 YR 6/4) moist; massive; soft, loose; slightly effervescent; moderately alkaline (pH 8.2).

Example 3.8 For a Mohall sandy loam soil profile, calculate the available water content (AWC) with the Soil Water Characteristics Calculator for each horizon down to 130 cm. Then, divide the soil into 20 cm increments, with a 30 cm increment at the top of the soil profile, such as might be necessary to correspond with moisture probe measurements. Calculate SWHC and RAW for the 20 cm layers, and then sum the SWHCs and calculate the RAW. Finally, calculate the number of days between irrigation events. In Table 3.3, p is 0.5; however, ET is high (1 cm/day) so MAD is reduced from 45 % to 50 %. The farm is in the desert and soil salinity is 3 dS/m

Estimation of parameters in soil layers.
The upper A horizon is defined by the name (Mohall sandy loam), and is not necessarily the same as the upper layer in the soil description. However, in this case, the upper layer in the Mohall description (course sandy loam) is the same. Use the Soil Water Characteristics Calculator (Fig. 3.11) to define the AWC. Because it is probably a coarse sandy loam, select the upper part of the Sandy loam (SaL) area, with 72 % sand and 10 % clay. At this soil texture, the FC is 13.8 % and the PWP is 6.8 %. Thus, the AWC is 8 % (Table 3.4). Because it is the surface layer, assume that the compaction is between loose and normal. There is no gravel in the soil description for the upper layer so that is zero. It is a desert soil, so assume that the organic matter fraction is just above zero.

The BA horizon is also a coarse sandy loam and has a blocky structure. Change to normal density and leave other

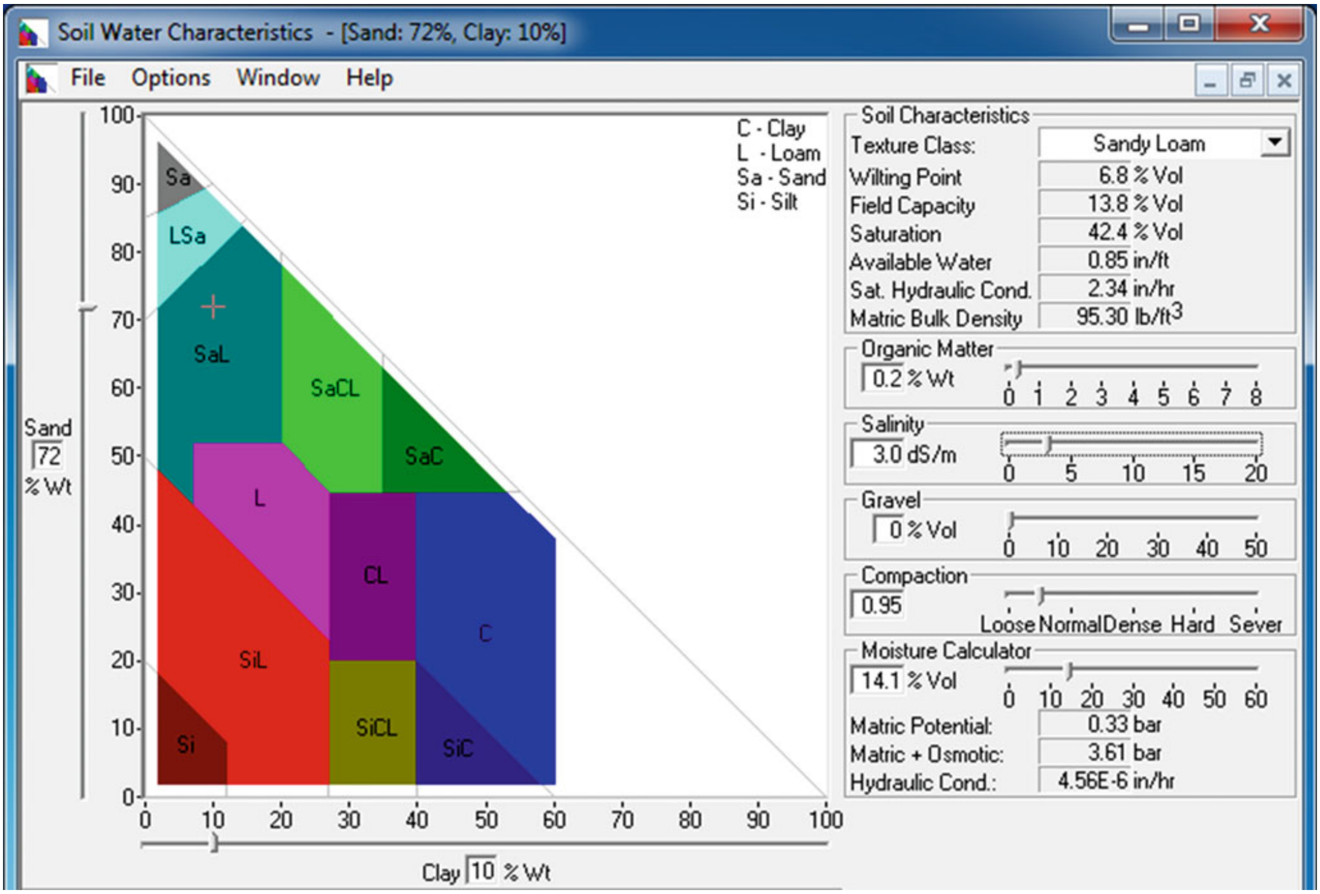

Fig. 3.11 Soil water characteristics calculator estimation of soil properties of upper layer of Mohall sandy loam soil

Table 3.4 Mohall sandy loam Available Water Capacity (AWC)

Horizon	Depth	Texture	AWC (%)
A	0–4 in (0–10 cm)	Coarse sandy loam	8.0
BA	4–10 in (10–25 cm)	Coarse sandy loam	6.6
Bt	10–19 in (25–48 cm)	Sandy clay loam	8.5
Btk1	19–27 in (48–58 cm)	Clay loam	12
Btk2	27–37 in (58–83 cm)	Loam	11
2Bk	37–54 in (83–137 cm)	Gravelly sandy loam	5.7

parameters the same in the HPC → PWP = 6.7%, FC = 13.3 %, and AWC = 6.6 %.

The Bt horizon is a sandy clay loam (Sand = 59 % and Clay = 28 %). The Bt horizon has a prismatic and blocky structure but it is 25–48 cm so increase the compaction to between normal and dense: SWCC → PWP = 17.2%, FC = 25.7 %, and AWC = 8.5 %.

The Btk1 horizon is a clay loam. The structure is blocky and prismatic so the AWC is at the upper, but the average depth is 60 cm so increase the compaction to dense: SWCC → PWP = 20.3%, FC = 32.3 %, and AWC = 12 %.

The Btk2 horizon is a loam (Sand = 42 % and Clay = 17 %). The soil has a subangular blocky structure, but the depth is 60 cm so characterize the compaction as dense: SWCC → PWP = 11.1%, FC = 22.2 %, and AWC = 11 %.

2Bk layer is a gravelly sandy loam (66 % sand and 10 % clay) with 20 % gravel; thus, move the gravel percentage to 20 %. It is a massive structure (no structure) so move the compaction to hard: SWCC → PWP = 6.4%, FC = 12.1 %, and AWC = 5.7 %.

Adjust Table 3.4 for measurement depths, and calculate SWHC for each layer (Table 3.5).

Table 3.5 Water holding capacity corresponding to neutron probe depths

Depth increment	Texture	AWC (%)	Depth of layer (cm)	SWHC/layer (cm)
0–30 cm (grav)	Sandy loam	7	30	2.1
30–50 cm	Sandy clay loam	8.5	20	1.7
50–70 cm	Clay loam and loam	12	20	2.4
70–90 cm	Loam and GSL	9	20	1.8
90–110 cm	Gravelly sandy loam	5.7	20	1.4
110–130 cm	Gravelly sandy loam	5.7	20	1.4

Table 3.6 Saturated conductivity (steady state infiltration rates) for different soil textures

Texture		Sand	Sandy loam	Loam	Clay loam	Silty clay	Clay
Average infiltration rate	(mm/hr)	50	25	13	8	2.5	0.5
Range	(mm/hr)	(25–250)	(13–76)	(8–20)	(2.5–15)	(0.5–5)	(0.1–1)

The SWHC or TAW for the entire root zone is 10.8 cm.

The RAW for the entire root zone is AWC(MAD = 10.8 cm (0.45) = 4.9 cm.

Thus, for 1 cm/day evaporation, there are approximately 5 days between irrigation events.

Infiltration

Infiltration (i) is the process of water from precipitation or irrigation entering the soil. The rate of infiltration (di/dt) can be described as the rate of change in ponded depth of water on the soil surface, which is called the Darcy velocity. If the rate of precipitation is less than the maximum infiltration rate of the soil, then water does not pond on the surface. The infiltration rate is initially high and then decreases over time to nearly steady state. Typical steady-state infiltration rates are given in Table 3.6. Notice the broad range of infiltration rates within each textural classification. In fact, the sand infiltration rate varies by an order to magnitude. This is why it is important to measure infiltration rates on the farm rather than rely on classifications.

An empirical model of infiltration over time can be developed by curve fitting infiltration data. One popular infiltration equation is the Kostiakov equation.

$$i = kt^{a} \tag{3.12}$$

where

i = depth of infiltration, mm
t = time, hr
k, a = constants.

Because the Kostiakov equation is an exponential equation, the coefficients can be calculated by taking the natural log of both sides of Eq. 3.13 and inserting two measured infiltration depths and times: two equations and two unknowns. The logarithm of infiltration rates is generally linear and fits the equation for the slope of a line in Eq. 3.14.

Table 3.7 Infiltrometer data

Time (min)	Depth of water (cm)	Infiltrated depth (cm)
0	15	0
10	13.9	1.1
20	13.1	1.9
40	11.8	3.2
60	10.6	4.4

$$\ln(i) = a\ln(t) + \ln(k)\ (y = mx + b) \tag{3.13}$$

$$y = mx + b \tag{3.14}$$

Infiltration rate can be measured with infiltrometers in which water is ponded above the soil surface, or disk permeameters, which create a negative potential above a porous plate placed on the soil surface. There are many types of ponded infiltrometers (single ring, double ring, furrow, etc.). After water is ponded in an infiltrometer, the depth of water in the cylinder vs. time is recorded. Double ring infiltrometers (Fig. 20.8) have two concentric cylinders, and it is assumed that infiltration in the inner cylinder, where depth is measured, is vertical. Automated infiltrometers add water to the infiltrometer with a float valve and record the volume of water addition to the infiltrometer over time. An entire furrow or a furrow section can be used as an infiltrometer: a volume balance (in – out = infiltration) can be used to estimate the rate of infiltration into a furrow section if the depth is constant.

Example 3.9 Calculate k and a in the Kostiakov equation for the ponded infiltrometer data in Table 3.7.

Take the natural log of time and infiltrated depth (Table 3.8). For example, the natural logs of time and infiltrated depth after 10 minutes are calculated as follows.

Table 3.8 Natural logarithm of data

Time (min)	ln (time)	ln (Infiltrated depth)
0		
10	2.302	0.0953
20	2.995	0.642
40	3.689	1.16
60	4.094	1.48

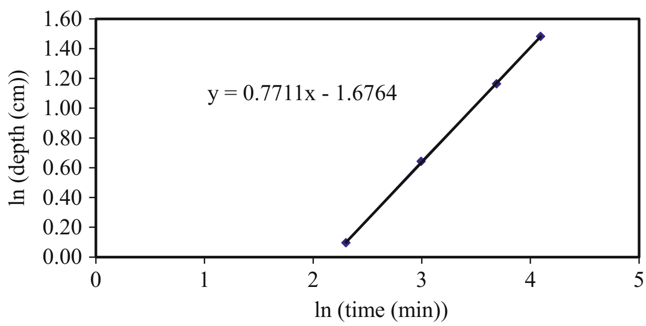

Fig. 3.12 Regression of logarithm data

$$\text{Infiltrated depth} = 15\text{ cm} - 13.9\text{ cm} = 1.1\text{ cm.}$$
$$\ln(i) = \ln(1.1\text{ cm}) = 0.095$$
$$\ln(t) = \ln(10\text{ minutes}) = 2.3$$

The line formed by the natural log data has slope 0.77 (Fig 3.12).

The slope (0.7711) is "a" in the Kostiakov equation. ln (i) = a ln (t) + ln (k).

Now solve for k by using the data from the 20-minutes infiltration point.

$$k = \frac{i}{t^a} = \frac{1.9}{20^{0.7711}} = 0.189$$

The short time represented by this infiltration example is generally not representative of the entire irrigation event, which may take 12–24 hours.

Instantaneous infiltration rate is the rate of water infiltration at any moment in time. The instantaneous Kostiakov infiltration rate is found by taking the derivative of Eq. 3.12 with respect to time.

$$di/dt = ak(t)^{(a-1)} \quad (3.15)$$

where

t = time, minutes
di/dt = infiltration rate, cm/min.

Soil surface storage can be added to the infiltration depth. If there are surface depressions, then water that does not infiltrate into the soil during a storm may be stored on the soil surface until it infiltrates. Typical soil surface storage

Table 3.9 NRCS intake family coefficients for equation 3–16 (c is 0.6985 for cm and 0.275 for inches for all intake families) for time, t, in minutes (After Cuenca 1989)

Intake family	a (cm)	a (in)	b
0.05	0.0533	0.0210	0.618
0.1	0.0620	0.0244	0.661
0.15	0.0701	0.0276	0.683
0.2	0.0771	0.0304	0.699
0.25	0.0853	0.0336	0.711
0.3	0.0925	0.0364	0.720
0.35	0.0996	0.0392	0.729
0.4	0.1064	0.0419	0.736
0.45	0.1130	0.0445	0.742
0.5	0.1196	0.0471	0.748
0.6	0.1321	0.0520	0.757
0.7	0.1443	0.0568	0.766
0.8	0.1560	0.0614	0.773
0.9	0.1674	0.0659	0.779
1.0	0.1786	0.0703	0.785
1.5	0.2283	0.0899	0.799
2	0.2753	0.1084	0.808
3	0.3650	0.1437	0.816
4	0.4445	0.1750	0.823

values are 1.2, 0.8, 0.2, and 0 cm for soils with slopes of 0–1, 1–3, 3–5, and >5 %, respectively (*NRCS NEH* values); however, these value depend on tillage method.

Soils have been classified by the Natural Resource Conservation Service (NRCS) by intake families. The NRCS equation for infiltration is a modified form of the Kostiakov equation.

$$i = a(t)^b + c \quad (3.16)$$

where

i = cumulative infiltration depth (cm)
a, b, c = constants
t = time after initiation of infiltration (min)

The c value was not included in the Kostiakov equation. This term represents initial infiltration into cracks and worm holes. This type of infiltration takes no time so it is not a function of t. It is assumed by the NRCS that c is the same for all intake families. However, c can be much larger for some soils. For example, most of the infiltration into swelling clay soils is into cracks. Once the cracks close within a few minutes, infiltration effectively ceases.

Intake family coefficients are listed in Tables 3.9 and 3.10. Although it is preferable to measure the infiltration rates on the farm with an infiltrometer or by observing the performance of a surface irrigation event, the intake families can be used for design. The NRCS intake families are groups of soils with similar intake rates and they are classified by saturated intake rate (inches/hour). NRCS soil maps list intake families for each soil, but these are rough guesses

Table 3.10 Soil intake families by surface texture (Credit NRCS)

	Intake family		
Soil texture	Sprinkler	Furrow	Border and basin
Clay, silty clay	0.1–0.2	0.1–0.5	0.1–0.3
Sandy clay, silty clay loam	0.1–0.4	0.2–0.8	0.25–0.75
Clay loam, sandy clay loam	0.1–0.5	0.2–1.0	0.3–1.0
Silty clay, loam	0.5–0.7	0.3–1.2	0.5–1.5
Very fine sandy loam, fine sandy loam	0.3–1.0	0.4–1.9	1.0–3.0
Sandy loam, loamy very fine sand	0.3–1.25	0.5–2.4	1.5–4.0
Loamy fine sand, loamy sand	0.4–1.5	0.6–3.0	2.0–4.0
Fine sand, sand	0.5+	1.0+	3.0+
Coarse sand	1.0+	4.0+	4.0+

rather than measured rates. Another method of estimating infiltration rate is to observe the rate of advance and recession during surface irrigation events (Chap. 20). For further information, I recommend the following papers (listed in references) that pertain to infiltration estimation. Clemmens and Bautista (2007) described some of the challenges and alternatives for estimating infiltration rates. Walker et al. (2006) described the development of modified NRCS intake families.

The infiltration behavior of soils can vary with irrigation method (Table 3.10).

The infiltration rate is found by taking the derivative of Eq. 3.16 with respect to time. Infiltration rate in cm/hr is found by multiplying Eq. 3.17 by 60.

$$\mathrm{di/dt} = \mathrm{ab(t)}^{(\mathrm{b}-1)} \tag{3.17}$$

where

t = time, minutes
di/dt = infiltration rate, cm/min.

Example 3.10 Calculate instantaneous infiltration rate (cm/hr) and cumulative infiltration (cm) vs. time, and plot both curves for the first 60 minutes after infiltration begins for intake family 4 – sandy soil.

The depth of infiltration after 60 minutes is $i = 0.4445\,(60)^{0.823} + 0.6985 = 13.6$ cm

Infiltration rate after 60 minutes is

$$\begin{aligned}\mathrm{di/dt\ (cm/hr)} &= 60 * \mathrm{ab(t)}^{\mathrm{b}-1} \\ &= 60 * 0.4445 * 0.823(60)^{(-0.177)} \\ &= 10.6\ \mathrm{cm/hr} = 106\ \mathrm{mm/hr}.\end{aligned}$$

The infiltration rate in Fig. 3.13 is approaching 10 cm/hr (100 mm/hr). This is within the range listed for sand in Table 3.6 (25–250 mm/hr). It is also equal to 4.0 inches per hour, which is the same as the intake family name. The names of intake families are based on their steady state infiltration rate, in/hr.

Saturated hydraulic conductivities are also estimated in the Soil Water Characteristics Calculator. For example, a sandy loam soil has a saturated hydraulic conductivity of 2.34 in/hr, which would be in between and intake family 2 and intake family 3 soil; Another method of estimating infiltration rate is to observe the rate of advance and recession during surface irrigation events (Chap. 20).

Soil Moisture Sensors

Management of systems is improved by feedback. Many sensors have been developed that detect plant and soil moisture status, which enable the grower to more accurately assess plant water requirements and irrigation scheduling. Most are in-situ (in contact with the soil) sensors. The advantage of in-situ soil moisture sensors is that they measure soil moisture change before the crop begins to experience stress. The disadvantage is that they must be physically placed in the soil, monitored, and possibly removed if they are in the way of cultivation operations. A second disadvantage is that many provide an inaccurate estimate of soil moisture status because of small sample volume, poor design, or poor installation.

Tensiometers have a porous ceramic cup in content with the soil, and they directly measure soil water potential. The normal operating range is −0 to −80 kPa (−0 to −0.8 atm or bar). They are suitable for drip irrigated crops where the water potential does not become extremely negative. They are sometimes wired to drip irrigation controllers in order to automatically trigger an irrigation.

Electrical resistance is inversely related to soil moisture content. The most common electrical resistance devices are gypsum blocks with electrodes inside the blocks. The effective range of gypsum blocks is −150 to −600 kPa (−1.5 to −6 bar). The disadvantages of gypsum blocks include slow response to changes in soil water content, sensitivity to soil salinity, chemical degradation, possible damage by field equipment, and insensitivity to soil moisture potentials less negative than −1 bar.

Heat dissipation devices measure matric potential in a porous material that is buried in the soil and is in hydraulic equilibrium with the soil. The porous medium contains a heating element and temperature sensor in the center. The temperature in the porous medium is measured, then the heating element gives a small heat pulse, and the temperature is measured again. The rise in temperature depends on the amount of water present in the porous material (less water means a larger rise in temperature). These sensors are more durable than gypsum blocks. They are insensitive to soil temperature and

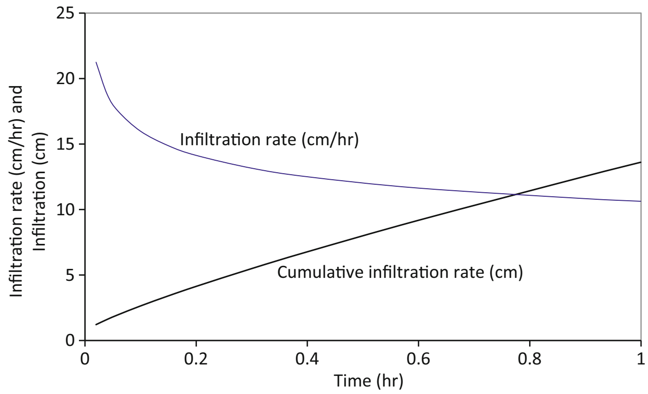

Fig. 3.13 Cumulative infiltration and infiltration rate for intake family 4

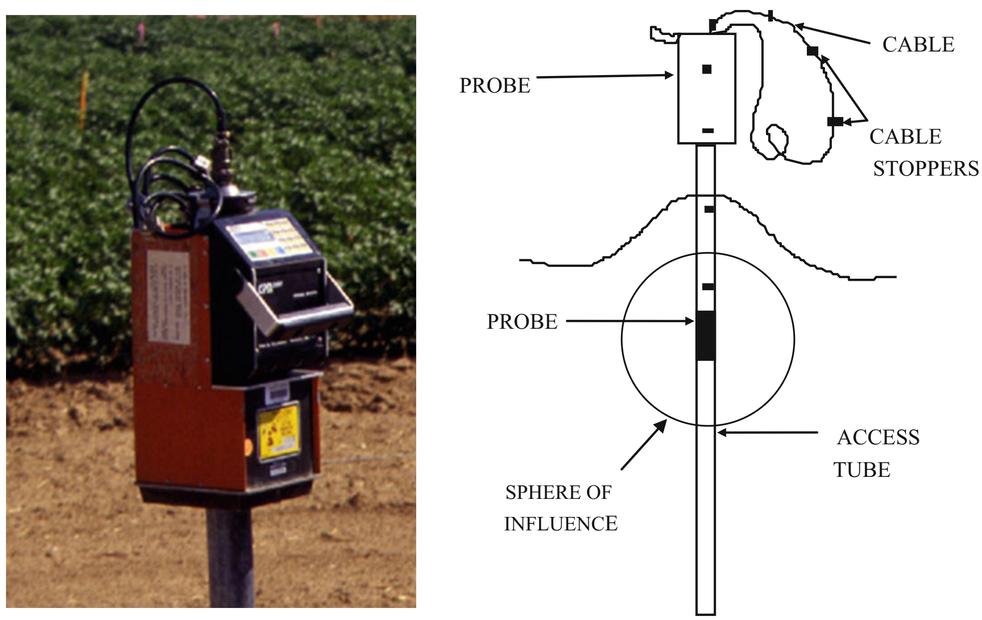

Fig. 3.14 Neutron probe and access tube (Credit Paul Colaizzi, USDA-ARS)

salinity, and seldom, if ever, require recalibration. They perform best at matric potentials less negative than −3 bar.

In a study by Evett et al. (2009), the neutron probe was recommended as the only practical, consistent, and accurate soil moisture measurement device for irrigation management. Electromagnetic sensors were found to be consistently inaccurate. The neutron probe (Fig. 3.14) consists of a sealed neutron source (Americium, Plutonium, or Radium mixed with Beryllium). The probe is lowered into an access tube (typically a 2-inch aluminum pipe). Neutrons emitted from the probe scatter into the surrounding soil, collide with hydrogen atoms in water molecules, and bounce back toward the probe. Since hydrogen atoms have the same mass as a neutron, a neutron will lose kinetic energy after colliding with hydrogen. Neutrons are then slowed down, and a detector tube (boron tri-fluoride) can count them over a specified time interval (15–30 seconds). The detector is not sensitive to fast neutrons bouncing back from large soil molecules.

There are several advantages to neutron probes. They are accurate over a large range of soil moisture, they can measure soil moisture at lower depths (1–3 m), and they are practically maintenance free. They also measure a much larger soil volume than other sensors so they provide a better estimate of the overall field moisture content. The neutron probe access tubes, when placed in center of beds, seldom interfere with field equipment. There are also several disadvantages to neutron probes. In field locations that require tillage, neutron probe tubes must be installed with a Giddings soil corer before and removed after each growing season. The access tubes can be buried below the soil surface during tillage if they have extensions at the soil surface that can be removed. RTK GPS (accurate to a cm) makes it easier to bury and find the access tubes after tillage. Neutron probes are time and labor intensive. It takes approximately 6 minutes to read 10 readings from one tube. Finally, the neutron scattering "sphere of influence" requires the probe to be 40–60 cm below the surface before readings are accurate, but most of the soil water content change occurs above 60 cm when sprinklers and drip systems are used. Last, but not least, neutron probes are radioactive, requiring substantial safety training and bureaucracy. However, the level of radiation is not dangerous if used correctly.

Neutron probes are calibrated by measuring the gravimetric water content at each depth from the soil removed from a new access hole. The calibration is made by setting a regression line through the neutron probe count number vs. soil water content measurements (measured by drying soil in oven). Neutron counts are then related to volumetric soil moisture by Eq. 3.18.

$$\theta_v = m\frac{x_n}{x_s} + b \tag{3.18}$$

where

θv = volumetric soil moisture
m = the slope
x_n = field count
x_s = average of all standard counts
b = the intercept.

Because the neutron source radioactivity decreases over time, a series of standard counts must be taken with the neutron probe inside the neutron probe housing before each day's measurements.

Field capacity can be estimated with a neutron probe by collecting measurements a few days after irrigation (after the field has drained). The lower limit of soil moisture, permanent wilting point can be estimated based on soil texture.

There are many types of capacitance measurement devices. Time domain reflectometers (TDR) are the most popular. In the past they have been very expensive; however, new models are less expensive and provide more consistent data. The original TDR probes consist of a buried probe, cable, and the TDR instrument which sends a single electromagnetic pulse down the cable to the probe. The pulse is reflected back to the instrument as a wave. The shape of the wave indicates the water content and salinity.

Example 3.11 Data in Table 3.11 was collected three days after irrigation. Field capacity for 40 cm depth is calculated below and field capacities for other depths are shown in Table 3.11.

$$\theta_v = 0.1823\frac{22043}{13308.1} - 0.03429 = 0.268 = 26.8\%$$

Questions

1. What is the textural class name of a soil that has 40 % clay, 20 % sand, and 40 % silt?
2. What is the textural class name of a soil that has 35 % clay, 15 % sand, and 50 % silt?
3. Download the Soil Water Characteristics calculator from the website listed in the References, and calculate the field capacity and permanent wilting point for the soil described in question 2. Use the field capacity and permanent wilting point values to calculate AWC.
4. Use the Soil Water Characteristics Calculator to determine whether Field Capacity or Permanent Wilting Point changes more with soil compaction and explain why. What is the percent change from Loose to Hard.
5. Use the Soil Water Characteristics Calculator to evaluate changes in Field Capacity or Permanent Wilting Point from zero to 8 % organic matter. Make sure your salinity is below 5 dS/m. Is the change greater for a sandy loam or a clay? Does the change increase the AWC?
6. A soil sample is removed from the field and weighed (130 g). The soil is then dried and the weight is 100 g. What is the gravimetric water content?
7. If gravimetric water content θ_{grav} is 30 % and bulk density ρ_b is 1.30 g/cm^3, then what is the volumetric water content? What is the porosity?
8. What is the FC, PWP, and AWC of a sandy loam? Use the Soil Water Characteristics Calculator (0 % and 4 % organic matter, salinity = 3 dS/m, gravel = 0 %, and compaction is normal. Discuss the impact of properties other than soil texture on hydraulic properties.
9. What is the depth of readily available water (RAW) for sandy loam (4 % organic matter) if the effective root zone depth is 1.5 m and MAD = 0.4?
10. Define MAD and answer the following questions. What is meant by 40 % MAD? Does 40 % MAD have a water content closer to PWP or FC?
11. What is the percent depletion if measured water content is 19 %, field capacity is 25 % and permanent wilting point is 10 %? If the MAD is 50 %, at what water content must the next irrigation take place? If the root zone depth is 1.5 m, then what depth of available water remains for plant use before the next irrigation? If evapotranspiration rate is 1 cm/day, then what is the maximum length of time before the next irrigation?
12. How much irrigation water (ft) should be applied in the next irrigation if porosity is 50 %, field capacity is 27 %, and permanent wilting point is 12 % in all layers? Measured soil water content in the upper 4 ft of soil (root zone) is as follows: 0–1 ft = 21 %, 1–2 ft = 22 %, 2–3 ft = 17 %, and 3–4 ft = 22 %. Assume that the irrigation efficiency is 100 %. Redo assuming that the irrigation efficiency is 80 %.
13. What is the depth of available water in the root zone if the readily available water in the root zone 1 week ago was 10 cm and the rate of evapotranspiration was 1 cm/day? During this time, a storm added 2 cm water to the soil. When should the next irrigation take place?
14. Use the Web Soil Survey (WSS) to find a soil at the agricultural field station in your area (or a location

Table 3.11 Neutron probe readings taken three days after irrigation

DAYS AFTER IRRIGATION		3	
Calibration Slope = m		0.1823	
Calibration Intercept = b		−0.03429	
Average of standard counts =		13308.1	
Standard counts	Depth	Field counts	Moisture content
13,340	40 cm	22,043	26.8 %
13,153	60 cm	12,354	13.5 %
13,160	80 cm	13,012	14.4 %
13,376	100 cm	11,243	12.0 %
13,330	120 cm	10,142	10.5 %
13,300	140 cm	10,876	11.5 %
13,015	160 cm	10,564	11.0 %
13,394	180 cm	10,743	11.3 %
13,528	200 cm	9,876	10.1 %

specified by the instructor) and repeat Example 3.8 for your soil. First, go to the WSS URL listed in the References and click "Start Web Soil Survey" in the upper right corner. There are four tabs at the top of WSS. Find your location under the "Area of Interest (AOI)" tab. You can make the scaling process faster by using your mouse and outlining the location you are interested in. Then outline one field at the research station with the red area of interest rectangle tool (Second button from right along top). After outlining the area of interest, press the Soil Map tab at the top. The soils in the AOI are listed on the left. Click on the soil name for a short description of that soil. For a more extensive description, go to the Natural Resources Conservation Service Soil Series Descriptions at the URL listed in the References. Type in only the name of the series, but not the texture. Define the field capacity and permanent wilting with the Soil Water Characteristics Calculator Assume an appropriate crop in your area. Then calculate the RAW of the soil based on the MAD (Table 3.3) and root zone depth of the crop. Find the root zone depth in Table 3.2.

15. Estimate the long-term ponded steady-state infiltration rate for a sandy clay loam with the Soil Water Characteristics Calculator.
16. For the following infiltration data, determine the SCS intake family as shown in Example 3.3.

Time (min)	Infiltrated depth (cm)
0	0.6985
5	1.33
10	1.79
50	4.55
100	7.33
150	9.82
200	12.13

17. Calculate the depth of infiltration and infiltration rate over time and plot the two curves for an intake family 1.0 soil. Plot your infiltration rate curves in terms of cm/hr and in/hr and calculate out to 1,000 minutes. At what time is the intake rate equal to 1.0 in/hr? Is this the steady state intake rate?
18. Calculate the moisture contents in Table 3.11 in the upper four layers if the calibration slope is changed to 0.2. If permanent wilting point is 11 % in the upper four layers, calculate the total available water in the upper four layers assuming that the neutron measurements were taken a few days after irrigation. Calculate the readily available water in the upper four layers if MAD is 0.45.

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Natural Resources Conservation Service Soils Website with links to publications and other sites. http://soils.usda.gov/

Natural Resources Conservation Service Soil Series Descriptions http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/home/?cid=nrcs142p2_053587

Natural Resources Conservation Service Web Soil Survey http://websoilsurvey.nrcs.usda.gov/app/

Soil Water Characteristics Calculator: download from http://hydrolab.arsusda.gov/soilwater/Index.htm

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