# Soil Physics: A Review with Applications

**Five (5) CEUs in Soil and Water Management**

## Introduction

This self study is based on performance objectives developed for the 2002 Council of Soil Science Examiners Fundamentals Exam. Each performance objective (bolded text) is followed by a brief explanation of the performance objective and a practical application (where appropriate) of that performance objective.

## Performance Objectives, Explanations and Practical Applications

**Physical properties.**

**Define the USDA soil particle size classes**.

| Particle Size Class | Size, mm |
|---|---|
| sand | 2.0 to 0.05 |
| silt | 0.05 to 0.002 |
| clay | <0.002 |

Sand can be further broken down into subclasses from very coarse sand to very fine sand.

**Determine the textural class of a soil using both the right angle and equilateral soil textural triangles.**

The equilateral textural triangle shown below [from USDA Soil Survey Manual. 1993. Handbook 18] is used to determine soil textural class when any two of the soil separate percentages are known. The intersection of the lines for each soil separate occurs in the area outlined for the soil textural class (e.g. loam, silt loam, sandy loam, clay). To find the intersection follow the lines extending from the percentages until they cross. For instance a soil that is 20 percent clay and 60 percent silt is a silt loam.
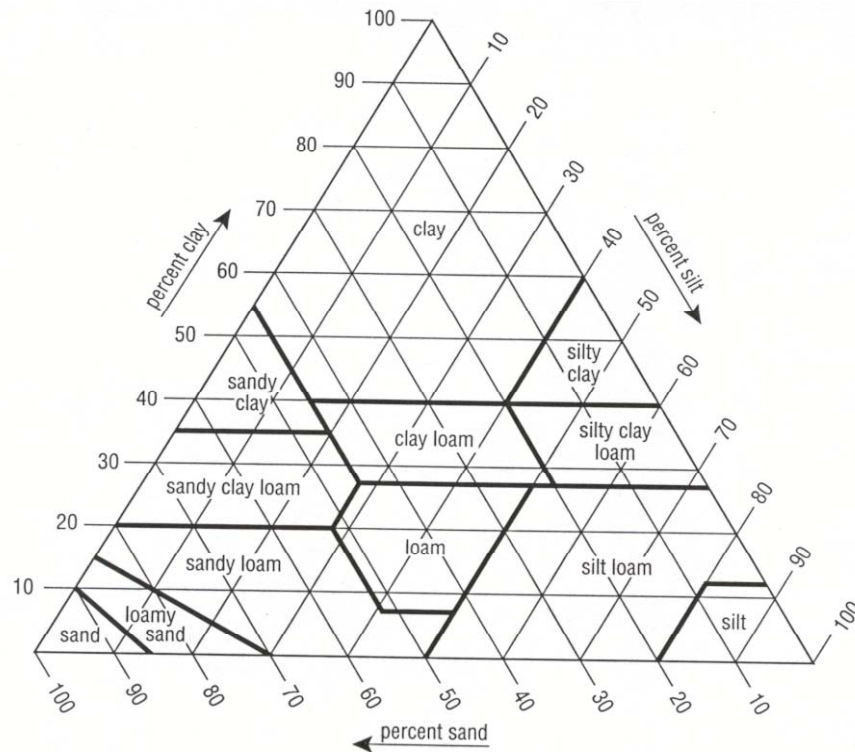
The right-angle textural triangle (below) is used in the same way as the equilateral textural triangle.
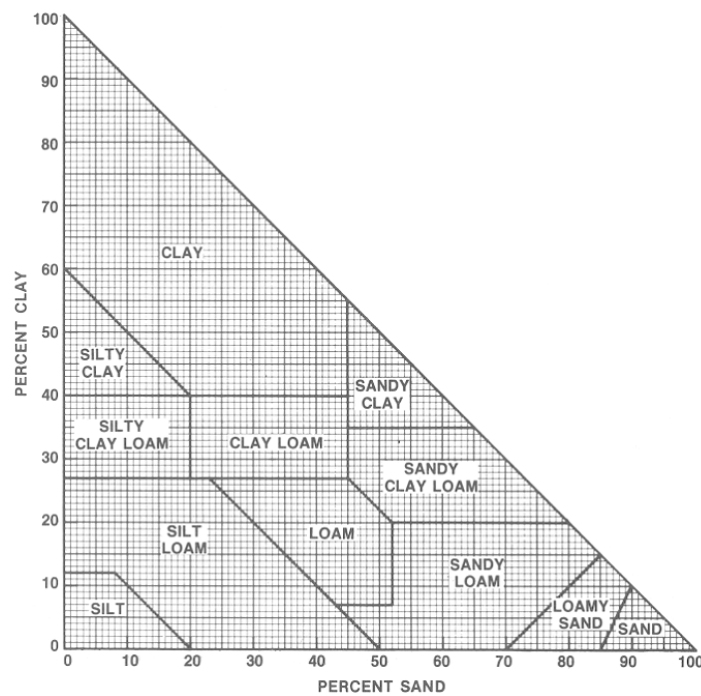
**Identify the range of sand, silt or clay content for any given soil texture using the soil textural triangle.**

This is done by extending a line from the sand, silt or clay edges (2) of a given soil textural class to the appropriate side of the triangle. For example, the clay textural class has from 55 to 100% clay, from 0 to 40% silt and from 0 to 55% sand.

Practical Application

Visual inspection of each textural triangle shows the relative impact of sand, silt and clay on soil properties. As little as 20% clay puts clay in the textural class name. To include silt in the class name, the soil must contain at least 40% silt, while at least 55% sand is required for sand to be part of the textural class. Thus, clay exerts by far the most influence on soil properties followed by silt and then sand. About one-third of the textural triangle is clay texture to further illustrate this point.

The textural triangle is also useful if you are given the textural class and need to know more about the relative amounts of sand, silt and clay in the soil. The triangle provides that information which can aid in understanding what the properties of a soil might be. For instance a loam usually has more sand and less silt than a silt loam, while clay contents are similar. Thus, a loam might be somewhat better drained and aerated than a silt loam all other things being equal.

**Define soil bulk density.**

Soil bulk density is the oven dry weight of soil divided by the soil volume. Units are $g/cm^3$.

BD = weight oven dry soil/soil volume

Remember that water content of soil is given on a dry soil basis, so dry soil weight is:

weight oven dry soil = weight of wet soil/(1 + BD/100)

An example:

A soil core is taken using a tube that has a 2 cm diameter and is 10 cm tall. The oven dried soil core weighs 45.4 g.

Volume = $\pi r^2 h$ = $\pi(1\ cm)^2$ (10 cm) = 31.4 $cm^3$

Bulk density = 45.4 g / 31.4 $cm^3$ = 1.45 g / $cm^3$

Practical Application

The bulk density of a soil is related to a textural class and organic matter content. Bulk densities typically range from less than 1 $g/cm^3$ to nearly 2 $g/cm^3$. Bulk densities less than 1 $g/cm^3$ are often soils that contain large amounts of organic matter. Clayey soils tend to have the smallest bulk densities of mineral soils, while sandy soil have the highest bulk densities. Silty soils are intermediate. Actual soil weights also include water.

One practical application is to estimate how much a give volume of soil weighs from bulk density and water content. A clay soil with 20% water by weight and bulk density of 1.2 $g/cm^3$ is compared with a sand soil (1.8 $g/cm^3$, 10% water by weight) in the example below for 5 cubic yard of soil (dump truck load).

clay soil:
[1.20 g wet soil/g dry soil](1.2 $g/cm^3$)(1 lb/454 g)(764,555 $cm^3/yd^3$)(5 $yd^3$) = 12,125 lb

sand soil:
[1.10 g wet soil/g dry soil](1.8 $g/cm^3$)(1 lb/454 g)(764,555 $cm^3/yd^3$)(5 $yd^3$) = 16,672 lb

The actual weight of soil varies with soil bulk density as shown in the table below.

| Texture | Bulk Density $g/cm^3$ | lb soil/acre | kg soil/ha |
|---------|-----------------------|--------------|------------|
| clayey | 1.2 | 1,630,000 | 1,800,000 |
| loamy | 1.5 | 2,040,000 | 2,250,000 |
| sandy | 1.8 | 2,450,000 | 2,700,000 |

lb soil/acre = (bulk density in $g/cm^3$)(1,359,533) for 6 inches of soil

kg soil/ha = (bulk density in $g/cm^3$)(1,500,000) for 15 cm of soil

A second practical application is to determine the weight of a nutrient, pesticide or other chemical of interest in a depth of soil. What is the difference in the amount of nitrate-N (lb/acre) in a clay (1.2 $g/cm^3$) versus sand (1.8 $g/cm^3$) soil if each contains 50 ppm nitrate-N? Soil depth is 6 inches. A proportion works well to solve this problem.

clay soil:

$$\frac{50 \text{ lb N}}{10^6 \text{ lb soil}} = \frac{X \text{ lb N}}{1.63 \times 10^6 \text{ lb soil}}$$ cross multiply and divide X = 81.5 lb N

sand soil:

$$\frac{50 \text{ lb N}}{10^6 \text{ lb soil}} = \frac{X \text{ lb N}}{2.45 \times 10^6 \text{ lb soil}}$$ cross multiply and divide X = 122.5 lb N

Thus, the same concentration of nitrate-N does not mean the same amount of nitrate-N. The amount is dependent on the bulk density of the soil.

**Define soil particle density.**

Soil particles are made up of many minerals and organic materials. As such there is considerable variability in the density of individual soil particles. The average value that is used in many calculations is the density of quartz, 2.65 g / cm$^3$.

PD = weight oven dry soil/particle volume

Practical Application

Particle density is used in calculations that follow.

**Define soil structure**.

The natural arrangement of soil particles (sand, silt, clay) into larger units (aggregates) of varying degrees of coherence is termed soil structure. These structural units are named peds. The major kinds of soil structure (or lack of structure) and some information on each structure type are presented in the following table [from USDA Soil Survey Manual. 1993. Handbook 18].

| Category | Shape | Description | Comments |
|---|---|---|---|
| structureless | single grain | soil particles act independently | typical for soils with high sand contents |
| | massive | soil particles cling together, but do not break into similar structural units | structure of puddled soils = soils which have lost structure |
| structured | platey | aggregates are thin and form like a stack of plates | |
| | prismatic | tall and column-like, sides are flat to rounded, tops are often flat and may not be distinct | |
| | columnar | tall and column-like, like prismatic except tops are rounded and distinct | |
| | blocky | irregular, six sided aggregates | angular blocky = sharp edges; subangular blocky = rounded edges |
| | granular | small round aggregates | common to plow layer |

Size of structural units (very fine to very coarse) and grade (weak, moderate, strong) are also used to describe soil structure.

**Describe the characteristics of soil structures above.**

See above.

<u>Practical Applicition</u>

Soil structure modifies soil texture.  For example, a clay soil in the structureless condition would have poor aeration, very limited infiltration and leaching, and water would pond on its surface.  That same texture with blocky structure would have good aeration, infiltration and could be leached.  Water could pond if the soil with blocky structure remained wet and structure was lost (not water stable).   The differences are due to the large pores that are created between the blocky clay aggregates.

**Explain how various tillage operations affect soil bulk density and pore space.**

Tillage can either increase or decrease soil bulk density depending on how tillage modifies soil porosity. Tillage at the proper soil moisture during seedbed preparation can substantially lower bulk density of the tilled soil due to the increase in pore space between granular structural units. The effect is only temporary and further tillage, other machine operations, and rainfall or irrigation often reverse the effect.

Tillage can increase soil bulk density at the depth of tillage by creating pans in certain soils. These pans will remain unless broken by subsoiling tools or other deep tillage implements.

Total pore space increases as bulk density decreases and vice-versa according to the equation.

$$\% \text{ Porosity} = (1 - (BD/PD)) \times 100$$

<u>Practical Application</u>

If the bulk density of a soil is known, the % porosity can be calculated.   Using the clay and sand soil examples, % porosities are calculated below.

clay soil:  % porosity = $(1 – (1.2 \text{ g} / \text{cm}^3/2.65 \text{ g} / \text{cm}^3)) \times 100 = 55\%$

sand soil:  % porosity = $(1 – (1.8 \text{ g} / \text{cm}^3/2.65 \text{ g} / \text{cm}^3)) \times 100 = 32\%$

Thus, 55% of the clay soil volume can be occupied by water and air, while only 32% of the sand soil volume can be occupied by water and air.  This means that at saturation, the clay soil could hold 6.6 acre-inches of water (0.55 x 12 acre-inches) for each foot of soil, while the sand soil could hold only 3.8 acre-inches of water.

How much water each of these soils will actually hold after a saturating rainfall or irrigation is also dependent on infiltration and drainage rates of each soil.

**Describe how soil texture and structure influence water movement and water holding capacity**.

Soil texture determines the pore size distribution within peds or aggregates, while structure determines pore size distribution between peds or aggregates.

Water movement in soils at or near saturation occurs mainly through the largest pores in the soil often termed macropores. Thus, water movement in these soils is controlled by both the texture and structure because both texture (e.g. sand) and structure (e.g. granular or blocky) create macropores. If a soil has medium to fine texture and no structure, macropores are few and water movement is slow even when the soil is very wet.

As a soil dries, water movement occurs in smaller and smaller pores or micro pores. At some point the movement is largely controlled by texture as little or no water is in the macro pores between structural units.

Pores size and tortuosity determine the resistance to water flow. Small pores have a higher resistance to flow than large pores and, so, small pores tend to limit water movement. Pore size also affects the water potential gradient. Overall water movement is a function of these two factors

Plant available water is that water which can be extracted by plants. The maximum value of available water is the difference between the amount of water the soil can hold after most free drainage has occurred (field capacity or water holding capacity) and the amount of water in a soil when plants will wilt and not recover even if water is added (wilting point or permanent wilting point). The field capacity and wilting point for several soil textural classes are shown below [adapted from Hanks, R.J. 1992. Applied Soil Physics. 2nd Edition. Springer-Verlag, New York].
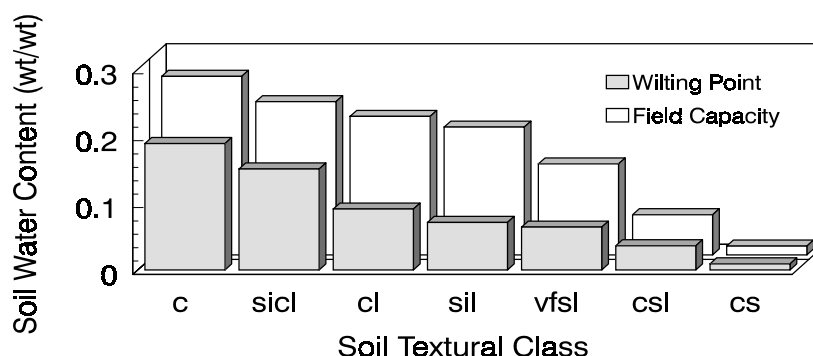


Note that plant available water is greatest for intermediate textures.

<u>Practical Application</u>

Available water changes with soil texture and does not necessarily increase as the clay content of a soil increases.  Actual measurement of available water using a water release curve (see below) is the most accurate method.

**Describe how soil texture, structure and water content affect thermal conductivity.**

*Reference:  R.J. Hanks.  1992.  Applied Soil Physics: Soil Water and Temperature Applications. 2nd Edition.  Springer-Verlag, New York.*

The thermal conductivity (K) of a soil is the amount of heat that soil will conduct under standard conditions.  Thermal conductivity increases as soil bulk density and soil water content increase. Water content is the more important property affecting thermal conductivity.  Soil texture and structure affect soil bulk density and, as a result, affect soil thermal conductivity.  As thermal conductivity increases, the change in soil temperature for a given amount of heat at the soil surface increases and vice-versa.

The heat capacity of a soil (c) is also dependent on the density of the soil and how much water the soil holds.  As soil becomes wetter, heat capacity increases.  As heat capacity increases, the change in soil temperature for a given amount of heat at the soil surface decreases.

Soil temperature is a function of thermal conductivity, heat capacity and the amount of heat at the soil surface.  Overall, a change in soil temperature (ΔT) can be described simplistically as,

$$\Delta T = (K/c) \, (HEAT)$$

The amount of heat absorbed at the soil surface (HEAT) is a function of weather, soil color and surface coverage due to plants and mulches.

<u>Practical Application</u>

Soils that are darker colored change temperature more quickly than soils that lighter colored because more of the heat at the soil surface is absorbed and less heat returns to the atmospere.

As a soil becomes wetter, temperature changes more slowly because the heat capacity of soil (c) changes more than the thermal conductivity of soil (K) for a given change in water content.

Soils that are prone to be cool in the spring can be identified with these principles in mind.  Cool soil often mean slow germination and seedling diseases.  Other biological processes such as decomposition of organic residues and mineralization of N from soil organic matter also slow as temperature decreases.

**Given two of the following, be able to calculate the third:  total soil volume, soil bulk density, and dry mass of soil.**

The relationship among bulk density (BD), dry soil mass (M) and soil volume (V) is:

$$BD = M/V$$

where units are $g/cm^3$.

Rearranging this equation,

$$M = BD \times V \text{ or } V = M/BD$$

Example:  A soil has a bulk density of  1.5 $g/cm^3$ and a volume of 10 $cm^3$, what is M?

$M = (1.5 \, g/cm^3)(10 \, cm^3) = 15 \, g$

Practical Application

To determine the bulk density of a soil, take a core of known volume, dry the core at 105˚C, and weigh the core.  Bulk density is the dry soil weight divided by the volume.  Once bulk density is known, a variety of calculations (see above) can be made.

**Describe the soil conditions conducive to surface crusting.**

Surface crusts form when rainfall (or irrigation) destroys surface soil structure followed by drying to form a physically resistant barrier or crust.  Rain drop impact alone can destroy the surface structure.  The lack of water stable aggregates in the soil lead to loss of structure upon wetting.

 Conditions that favor crusting are:

> excessive tillage which destroys soil structure
> high silt content which hinders structure formation
> lack of soil surface protection from rain drop impact
> low surface soil OM levels and few water stable aggregates
> high surface soil exchangeable Na  where soil is dispersed
> intense rainfall

Practical Application

Understanding what causes crusting can be used to identify management alternatives to prevent crusting.  Reducing tillage and increasing surface residues are two of the best.  The soil surface is protected, organic matter will increase (particularly under no-till), and soil structure will develop.

**Describe how soil color indicates soil physical, chemical, and biological properties.**

*Reference: F.R. Troeh and L.M. Thompson. 1993. Soils and Soil Fertility. 5th Edition. Oxford University Press, New York.*

Soil color or lack thereof is largely a function of organic matter content and minerals in a soil. Soil organic matter adds dark brown to black color to surface soil horizons. Iron minerals add red, yellow and brown colors to soil. The background color of the soil matrix without these coloring agents is often gray.

Soil physical properties such as drainage and aeration are a function of the pore size distribution in a soil. Soils that are dark brown (high OM) or reddish (ferric oxides) often have good structure and physical properties which lead to good drainage and adequate aeration. Yellowish soils are intermediate and gray soils are poorly drained and aerated. Soil temperature is also related to soil color as darker colored soils absorb more radiation than lighter colored soils.

Soil chemical properties such as CEC and state of oxidation may be related to soil color. Soils high in OM are dark colored and can have high CEC. Soil oxidation status follows the order red>yellow>>gray with the red soils being most oxidized and the gray soils being most reduced.

Soil biological properties such as microbial activity and the nature of the active microbial population are related to soil OM levels and soil aeration which are, in turn, related to soil color. Dark brown to black soils often have higher levels of soil OM. Soils that are well oxidized support an aerobic microbial population, while soils that are reduced are dominated by anaerobic microorganisms.

Practical Application

Usually more than soil color needs to be known to properly predict soil properties. The most helpful information is the source (e.g. organic versus mineral) or reason (e.g. clay mineralogy, wetness) for the color. With this information soil behavior can be inferred.

**Soil-water relationships.**

**Describe the gravimetric method of determining soil water content.**

A sample container is weighed (tare), wet soil is placed in the container and the container plus soil is weighed.

The soil is dried at 105EC to constant weight and the container plus dry soil is weighed.

The weight of water is the difference in the wet and dry soil weights.

Gravimetric water content ($\theta_{wt}$) is the weight of water divided by the weight of DRY SOIL.

$$\theta_{wt} = \text{weight of water/weight of oven dry soil}$$

Units are g/g or on a percentage basis (0.25 g/g = 25%)

Example:

25 g of wet soil is placed in a container weighing 2 g. After drying the container plus soil weighs 22 g. What is the $\theta_{wt}$ ?

> tare = 2 g
> tare plus wet soil = 27 g
> tare plus dry soil = 22 g
> weight of water = 5 g (27 g - 22 g)
> weight of dry soil = 20 g (22 g - 2 g)
>
> $\theta_{wt}$ = 5 g / 20 g = 0.25 g/g

**Given bulk density, convert gravimetric water content to volumetric water content.**

The equation shown below is used where units are $cm^3/cm^3$.

$$\theta_{vol} = (BD \, H \, \theta_{wt})/1.0 \text{ g/cm}^3$$

The units of BD are $g/cm^3$, while the units of $\theta_{wt}$ are g/g. Dividing the right-hand side of the equation by the density of water (1 $g/cm^3$), the units of volumetric water content become $cm^3/cm^3$.

Example:

A soil has a bulk density of 1.4 $g/cm^3$ and a gravimetric water content of 0.25 g/g. What is the volumetric water content?

$\theta_{vol}$ = (BD $H \theta_{wt}$)/1.0 g/cm$^3$ = (1.4 g/cm$^3$ H 0.25 g/g)/1.0 g/cm$^3$ = 0.35 cm$^3$/cm$^3$.

**Define field capacity.**

Field capacity is the amount of water held in a soil after it has been saturated and free drainage has ceased. Water potential at field capacity is about -0.33 bar or -33 kPa.

**Define permanent wilting point.**

Permanent wilting point is the amount of water held in a soil where plants wilt and will not recover when more water is added to the soil. Water potential at permanent wilting point is about -15 bar or -1,500 kPa for most crops.

Practical Application

The maximum amount of available water a given depth of soil can hold can be estimated from the differences in gravimetric ($\Theta_{wt}$) or volumetric ($\Theta_{vol}$) water content of the soil at field capacity versus permanent wilting point and the bulk density (BD) of the soil.

If water contents at field capacity and permanent wilting point are given gravimetrically (g/g), they can be converted to volumetric units ($cm_3/cm_3$) using the following equation.

$$\Theta_{vol} = \Theta_{wt} \times BD \text{ / density of water}$$

Then, the difference between the two volumetric water contents ($\Delta\Theta_{vol}$) is multiplied by the soil depth to give the depth of available water.

$$\text{inches of available water} = \text{inches of soil} \times \Delta\Theta_{vol}$$

For example, a soil has a field capacity of 0.3 g/g and wilting point of 0.1 g/g. The bulk density of this soil is 1.45 $g/cm^3$.

field capacity:  $\Theta_{vol} = (0.3 \text{ g/g})(1.45 \text{ g/cm}^3) / (1 \text{ g/cm}^3) = 0.435 \text{ cm}^3/\text{cm}^3$

permanent wilting point: $\Theta_{vol} = (0.1 \text{ g/g})(1.45 \text{ g/cm}^3) / (1 \text{ g/cm}^3) = 0.145 \text{ cm}^3/\text{cm}^3$
) $\Theta_{vol} = 0.435 \text{ cm}^3/\text{cm}^3 - 0.145 \text{ cm}^3/\text{cm}^3 = 0.29 \text{ cm}^3/\text{cm}^3$

inches of available water = 12 inches of soil x 0.29 = 3.48 inches of water

This is the maximum amount of available water for this soil.  At water contents lower than field capacity, substitute the actual water content for field capacity in the calculations.

Once the inches of available water is known, the length of time before a crop will wilt can be estimated by from the inches of available water and the atmospheric demand (evapotranspiration rate).  If the atmospheric demand is 0.25 inches/day, then 3.48 inches of available water will last 14 days (3.48 inches/0.25 inches/day).

**Use the soil moisture characteristic curve (soil water retention curve) to determine available water.**

A soil moisture characteristic curve is shown below.



Volumetric Water Content, $cm^3/cm^3$
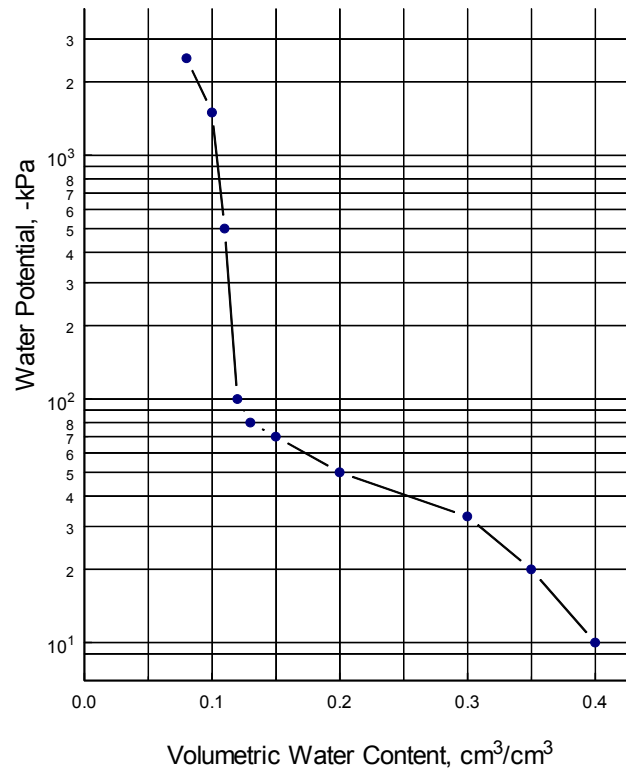
Available water (AW) is the difference between volumetric water content at field capacity (FC) and permanent wilting point (PWP).

$$AW = FC - PWP$$

In the example above, FC (-33 kPa) is about 0.3 $cm^3/cm^3$, while permanent wilting point (-1,500 kPa) is about 0.1 $cm^3/cm^3$. The difference is available water or 0.2 $cm^3/cm^3$.

This means that this soil profile holds 2.4 inches of available water in 12 inches of soil (0.2 H 12 inches).

Practical Application

If the soil moisture characteristic curve is available for a soil, estimation of field capacity, permanent wilting point, available water and times between irrigations can be determined.

**Identify the following components of the hydrologic cycle.**

The hydrologic cycle includes the components shown below.

> Precipitation (P):  rainfall and irrigation
> Evaporation (E):  water loss from soil surface
> Transpiration (T): water loss from plant surface
> Runoff (RO):  loss of water over the soil surface
> Infiltration:  Precipitation minus runoff
> Percolation:  downward movement of water especially when soil is wet
> Deep seepage (DS): downward movement of water below stored soil water zone
> Storage (S):  water in a give volume of soil

These components determine the change in stored soil water, storage, (ΔS) for a given volume of soil in the equation shown below.

$$\Delta S = P - E - T - RO - DS$$

Practical Application

Conceptually, water balances have use in determining the need for irrigation and the estimation of water/solute movement for a given time period.

Irrigation can be added to P to keep ΔS within limits for good crop growth.  To do this, estimates of E, T, RO and DS over the growing season must have been determined previously.

Solute movement via runoff or deep seepage can also be estimated from a water balance made over the appropriate time period.  The time period immediately following a rainfall or irrigation event is a good choice for these situations.  This is because movement of solutes present in the soil just prior to rainfall can be determined.   In other words, solute movement is rainfall or irrigation event dependent.

**Define:**

*Reference:  Glossary of Soil Science Terms.  1987.  Soil Science Society of America.*

Perched water table:  a water table above a saturated soil layer.  The saturated soil layer keeps the water from moving to the vadose zone (unsaturated layer beneath the saturated layer).

Ground water table:  the ground water surface where the soil is saturated.

Vadose zone:  unsaturated soil layer.

Capillary fringe:  the zone immediately above saturated soil where water rises by capillary action.

**List soil properties that affect water movement through the soil profile.**

Water movement through a soil profile is a function of the water potential gradient and the hydraulic conductivity of the soil profile (see Darcy's Law below).

The hydraulic conductivity of a layered soil profile is related to the thickness of each layer and the hydraulic conductivity of each layer. As the thickness of a layer increases and the hydraulic conductivity decreases (resistance to flow increases), the layer becomes more restrictive to water movement.

Layer thickness does not affect hydraulic conductivity as much as texture. For example a relatively thin clay layer can control water movement through a soil profile. This occurs because the clay layer has a small hydraulic conductivity that limits water movement.

Practical Application

If a soil has a coarse-textured layer over a fine-textured layer, the wetting front will move rapidly through the coarse textured layer and slowly through the fine textured layer because the fine-textured layer will have a much lower hydraulic conductivity. Water can perch at this textural boundary.

If a soil has a fine-textured layer over a coarse-textured layer, the wetting front will remain at the bottom of the fine-textured layer until fine-textured soil at the boundary is near or at saturation. Then, water will move rapidly into the coarse textured layer.

**Describe preferential flow in soils.**

*Reference: Miyazaki, T., S. Hasegawa, and T. Kasubuchi. Water Flow in Soils. Marcel Dekker, Inc., New York.*

Preferential flow is the rapid movement of water through various kinds of large pores in soil during infiltration.

There are various kinds of preferential flow:

> Flow through vertical or horizontal cracks, worm holes, root channels, etc.

> Rapid movement of water from a near-saturated or saturated, fine-textured surface layer to an underlying coarse-textured layer. Movement follows channels in the coarse-textured layer.

> A second case of the fine-textured layer over the coarse-textured layer occurs when the coarse-textured layer is inclined. Water flows along the layer boundary until a point where it moves rapidly into a channel in the coarse-textured layer.

<u>Practical Application</u>

Rapid movement of nutrients, pesticides and other solutes deep in the soil profile can occur where preferential flow occurs during and after a rainfall or irrigation. Such transport processes can have agronomic and environmental consequences.

**Water movement and transport processes.**

*Reference: H.D. Scott. 2000. Soil Physics – Agricultural and Environmental Applications. Iowa State University Press. Ames.*

**Define the following soil water potentials:**

Pressure potential ($R_p$): potential from a free water surface in or above a reference point in soil.

Matric potential ($R_m$): potential of water in soil pores in an unsaturated soil from adhesion (water/soil) and cohesion (water/water) at a given point in a soil. Increases as pores are smaller.

Gravitational potential ($Rg$): potential of water due to the force of gravity.

Osmotic potential ($R_o$): potential of water due to solutes in soil water at a given point in a soil.

Total potential: sum of pressure, matric, gravitational, and osmotic potentials.

The difference between the total potential at two points in the soil divided by the distance between those two points is the hydraulic head gradient (see Darcy's Law below).

<u>Practical Application</u>

There are several kinds of water potential in addition to gravity that can cause water to move in all directions in a soil. Recognizing this aids in understanding water and solute movement in soils.

**Determine the direction of water flow given soil water potentials.**

Water flows from areas of higher potential energy to areas of lower potential energy.

**Define Darcy's Law and its components.**

$$q = K\,(\Delta H/L)$$

where q is water flow between two points, $\Delta H$ is hydraulic head difference between the two points, and L is the distance between the two points. The quantity in parentheses is the hydraulic head gradient.

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**Describe how preferential flow can affect ground water quality.**

Preferential flow can be the dominant flow mechanism in a soil. If a solute such as nitrate or a soluble pesticide is at the soil surface and has not entered soil aggregate interiors, rainfall or irrigation can transport the solute to a much deeper soil depth than would be predicted if a normal wetting front moved through the soil. The solute can then move to groundwater rapidly.

**Describe how leaching potential differs between nitrate-nitrogen and ammonium-nitrogen in soils of different textures.**

Nitrate-N ($NO_3^-$) is an anion that is not adsorbed by most soils due to low soil AEC. Nitrate-N is repelled from soils with high smectite content due to the high negative charge on the CEC.

Ammonium-N ($NH_4^+$) is a cation that is adsorbed by soil CEC and can be fixed by illite.

Leaching potential is a function of the interaction of either ion with clay and OM surfaces and with the amount of downward mass flow or preferential flow of water.

Sands have small cation and anion exchange capacities and large pores. Thus, nitrate-N and ammonium-N interact little with the soil and leaching proceeds rapidly during infiltration of water.

Loams retain ammonium-N, but not nitrate-N. When leaching occurs in these soils, nitrate-N moves with the drainage water. Little leaching of ammonium-N is expected.

Clays may have more rapid leaching of nitrate-N than the rate of drainage because nitrate-N is repelled from the negatively charged clay surfaces causing the concentration in drainage water to be larger than the nitrate-N in all soil water. Water movement through a clay will likely be slow, however. Little leaching of ammonium-N is expected.

**Explain how plant residues on the soil surface affect surface runoff and infiltration.**

Plant residues on the soil surface protect the soil surface from raindrop impact and create surface roughness. Protecting the soil surface from raindrop impact decreases the potential for surface crusting and loss of infiltration capacity. Increasing surface roughness retains water allowing more infiltration.

As infiltration increases, runoff decreases for a given rainfall or irrigation event.

**Describe the relationship between saturated hydraulic conductivity and soil pore size distribution.**

The hydraulic conductivity of a soil is function of the pore size distribution of a soil that also determines the porosity of a soil.

The resistance to water flow increases as pore size decreases and tortuosity increases. Tortuosity is a measure of the path length of a pore over a given length of soil. Thus, soils

with small, tortuous pores have lower hydraulic conductivities than soils with large, non-tortuous pores.

Clays have a high porosity and low hydraulic conductivity because clays have numerous, yet very small pores.  Sands have a low pore space and high hydraulic conductivity because sands have large pores.  Thus, hydraulic conductivity and soil porosity tend to be inversely related if the only consideration is soil texture.  If soil texture is constant and soil structure creates large pores in a soil, porosity and hydraulic conductivity increase.

**Describe how water infiltration and percolation are affected by:**

Infiltration is the movement of water into the soil, while percolation is the movement of water through soil.  Infiltration and percolation rates increase as the soil pore size increases and water entering the soil surface moves downward away from the soil surface rapidly.  Thus, soil textures with larger pores (sands) tend to have higher infiltration rates than soil textures with smaller pores (clays).  As soil structure at the soil surface increases and if the subsoil has good structure, improved infiltration and percolation are favored.  Since soil organic matter often improves soil structure, soils with higher levels of organic matter would be expected to have higher infiltration and percolation rates.

As bulk density decreases total porosity increases, but the pores are smaller limiting infiltration and percolation.  As particle density decreases, total porosity increases, and pores are often larger (e.g. organic soils, cinder soils) with good infiltration and percolation.  As pores in soils are more tortuous, infiltration and percolation decline.

**Soil temperature.**

**Describe how the following affect soil temperature:**

*Reference:  Hanks, R.J. 1992. Applied Soil Physics: Soil Water and Temperature Applications.  Springer-Verlag, New York*.

Soil temperature is a measure of the intensity of heat in soil.

Soil temperature is affected by:
    heat exchange with air or the atmosphere
    heat flow in soil
    consumption or production of heat in soil

Soil temperature is affected by soil moisture in two ways:

Wetter soils have larger heat capacities so they must absorb more heat than drier soils for a given change in soil temperature.  In general, wetter soils will be cooler because of this.

Wetter soils have more evaporation that dissipates heat and cools the soil.

*Reference: H.D. Scott. 2000. Soil Physics – Agricultural and Environmental Applications. Iowa State University Press. Ames.*

Soil temperature is affected by <u>soil color</u> in that lighter colored soils reflect more heat than darker colored soils. Thus, if two soils have similar properties and water contents, the darker soil will warm more quickly. Interestingly, this is often not the case because darker soils may be wetter due to higher soil organic matter contents.
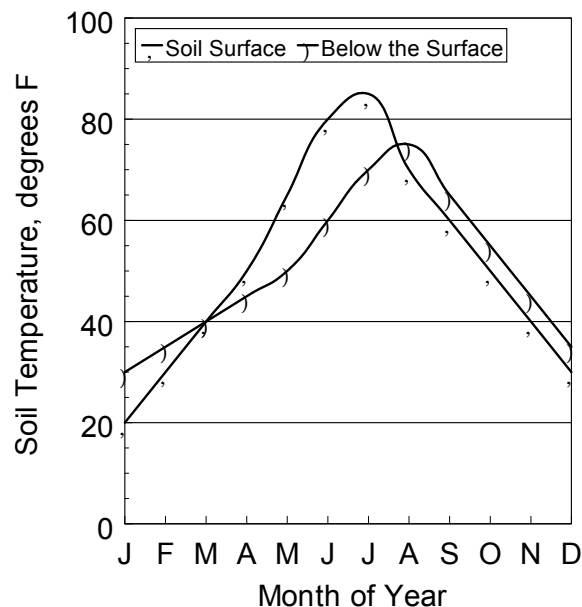
<u>Practical Application</u>

When soil temperature changes, the rates of biological, chemical or physical processes change. Microbial activity increases or decreases as temperature increases or decreases. Thus, the many microbial processes (e.g. mineralization, immobilization, decomposition, oxidation, reduction, nitrification, denitrification) change rate as temperature changes. Chemical processes like the rate of formation of new minerals changes as temperature changes though the reaction rate does not always increase with a temperature increase and vice-versa. Physical processes like volatilization also change with temperature. As temperature increases the rate of these physical processes increases.

Often, a reaction rate will increase (or decrease) 2 to 3 times for a 10°C (18°F) temperature change.

**Describe how soil temperatures change at different depths in response to seasonal temperature fluctuations.**

In general, soil temperatures at depth will lag behind surface soil temperatures. In addition, the range in soil temperatures decreases with soil depth. Both effects are shown in the graph below.

Since subsoil temperature lags surface soil temperature, subsoil reaction rates will also lag surface soil reaction rates.  Many other factors also influence reaction rates in the subsoil.  For microbial processes, the lack of organic matter and smaller microbial population are important.

**Explain how soil temperature affects the rate of  microbial and chemical processes in the soil.**

From about 15EC to 35EC, rates of microbial and chemical processes increase 2 to 3 times for each 10EC temperature increase.

Below 15EC, reaction rates decline to zero at 0EC.

Above about 35EC, reaction rates may decline for microbial processes, but not for chemical processes.

**Soil gases**.

*Reference: H.D. Scott.  2000.  Soil Physics – Agricultural and Environmental Applications.  Iowa State University Press.  Ames.*

**Explain how soil aeration is affected by:**

Bulk density:  As bulk density (BD) decreases soil porosity increases and vice versa.  High bulk densities are characteristic of sandy soils, while low bulk densities are characteristic of clayey soils.   Soils with low bulk densities have many small pores, while soils with hight bulk densities have few large pores.

Particle density:   As particle density decreases, soil porosity increases and vice versa according to the equation:  % Porosity = 100 – (BD/PD)$\times$100.

Structure:  Soil structure modifies soil texture by creating pores between aggregates.  These pores are often large and filled with air.

Practical Application

The volume of soil filled with air decreases from sandy to clayey soils at field capacity.  As soils dry, the small pores in clayey soils fill with air and clays may have more air filled volume than sand.

**Explain how irrigation or rainfall affects soil oxygen content**.

Irrigation or rainfall infiltrate and fill soil pores that previously contained gases.  These soil gases are moved to the atmosphere during infiltration.  After drainage occurs, atmospheric gases reenter the soil.

This process increases soil oxygen content because oxygen levels in the displaced soil air are lower than atmospheric oxygen levels which replace it.

**Explain how soil texture and/or structure affect soil gases movement.**

Soil gases move in response to a gradient and the resistance of the soil to flow.

Soil gases move through soil pores by mass flow when the gradient is a total pressure gradient as would occur during rainfall, irrigation or barometric pressure changes.

When the gradient is a partial pressure gradient for a particular gas that gas moves through soil pores by diffusion.

Soil texture affects the resistance of gas flow by mass flow or diffusion.  Small, tortuous pores found in fine-textured soils exhibit a higher resistance to gas flow than the large pores in a coarse-textured soil.  Soil structure modifies these effects by creating large pores between soil aggregates or peds.

Practical Application

Gas exchange in soils is most rapid in large pores.  Soils dominated by small pores exhibit slow gas exchange.   Where gas exchange is slow and the soil is wet, oxygen used by aerobic microbes is replaced slowly, and the soil can become anaerobic and carbon dioxide accumulates.   While this can also occur in soils with larger pores, usually the soils with larger pores (better aeration) must be wetter in a relative sense.

**List the relative range of concentrations of the following soil gases under aerobic and anaerobic conditions.**

| Soil Gas | Aerobic Conditions | Anaerobic Conditions |
|---|---|---|
| Oxygen | 1 – 21% | none |
| Carbon dioxide | 1 – 10% | Often higher than aerobic case |
| Water vapor | <1% | n/a |
| Nitrogen | 78% | 78% |
| Methane | Trace | Trace unless highly reduced |

**Explain how soil gas movement is affected by:**

Bulk density, particle density, porosity, and structure affect gas movement through their impact on pore size, pore distribution and pore tortuosity as has been described above. Gases can move by mass flow during rainfall events when aerated soil pores are filled with water, or by diffusion.  When gases move by mass flow, the greater the number and volume of large pores, the more rapid the gas movement.  When gases move by diffusion, the concentration gradient of the gas and the resistance of the soil pores to gas movement (diffusion coefficient) determine the rate.  As more large pores are present, the diffusion coefficient decreases and vice versa.  The impact on concentration gradient is less clear.

**Engineering properties.**

**Compare the shrink-swell potentials of soils composed of kaolinite and smectite clays.**

*Reference:  Mitchell, J.K. 1993.  Fundamentals of Soil Behavior. 2nd Edition.  John Wiley & Sons, Inc., New York.*

The amount of shrink-swell in a soil depends upon the clays present and the amounts of each clay.  In addition, the changes in soil water content and in the cations on the clay surfaces and in the soil solution have significant effects.

Shrink-swell behavior in a soil follows the following trends:
> more smectite = more shrink-swell
> more kaolinite = less shrink-swell
> lower valence cation on CEC (eg. $Na^+$ versus $Ca^{2+}$) = more shrink-swell
> lower soluble salts in soil solution = more shrink-swell

Practical Application

As shrink-swell increases, other soil properties also change.  Increased shrink-swell is associated with lower infiltration and drainage (unless the soil is dry and cracked), a narrow range of water contents at which the soil can be tilled, stickiness, and excessive wetness during wetter parts of the year.

**Describe how soil compaction affects infiltration, permeability, bulk density and thermal conductivity.**

Compaction destroys soil pores created by structure.  Pore size distribution changes in the direction of more, smaller pores.  As a result, soil compaction decreases infiltration, decreases permeability, increases bulk density, and increases thermal conductivity.

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