Soil Water: Characteristics and Behavior

Soil Water

Soil-water relationships are important because:

- Plants need water for survival due evaporation
- Water contains necessary plant nutrients in the soil solution
- Soil moisture helps regulate soil temperature and soil air
- Determines the incidence of erosion

Soil Water

- Water expands when it freezes
- Dissolves many salts, some non-polar compounds
- Does not dissolve many organic compounds
- Participates in many chemical reactions at ambient temperatures
- Soil water relationships based in large part on soil geometry (or structure)

STRUCTURE AND PROPERTIES OF WATER

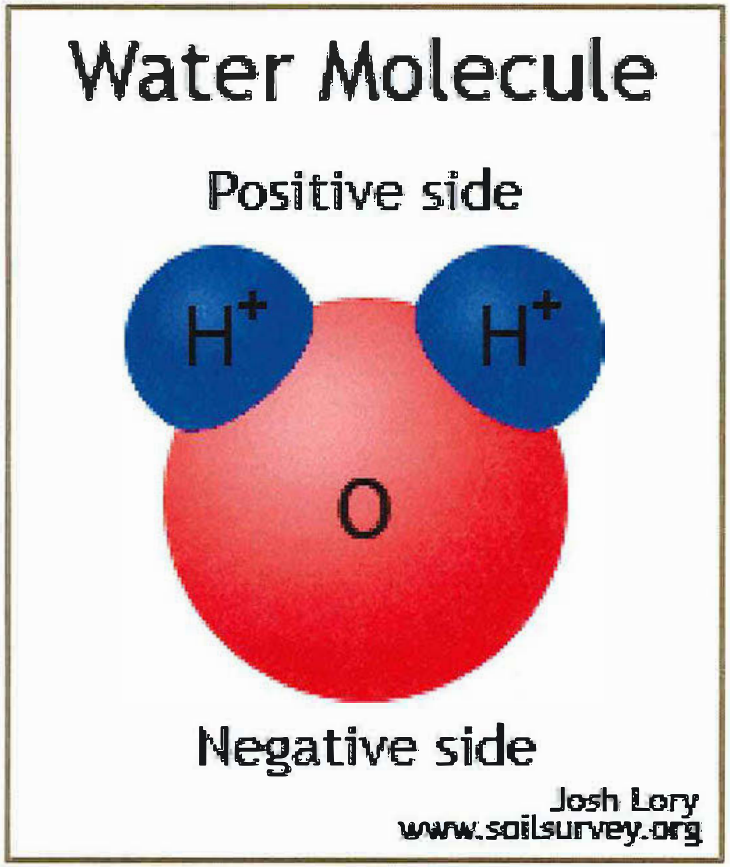
- The ability of water to influence so many soil processes is determined primarily by the structure of the water molecule
- Atoms are bonded covalently
  - Each Hydrogen atom shares its single electron with the Oxygen atom

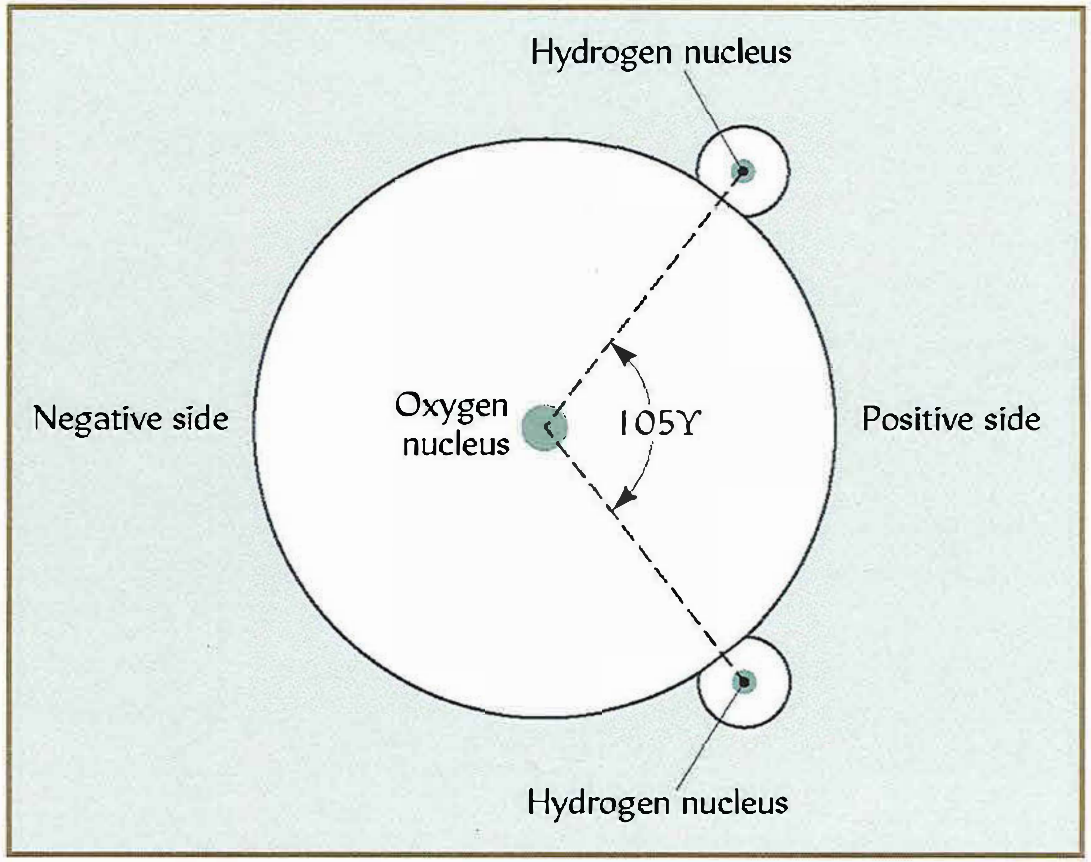
Structure and Properties of Water

Polarity

- Water is a V-shaped polar molecule with one side positively charged, the other negatively charged
  - Allows water molecules to attach to neighboring water molecules
  - Negative (oxygen) end attracts cations
  - Positive (hydrogen) end attracted to negatively charged clay surfaces

Two-dimensional representation of a water molecule

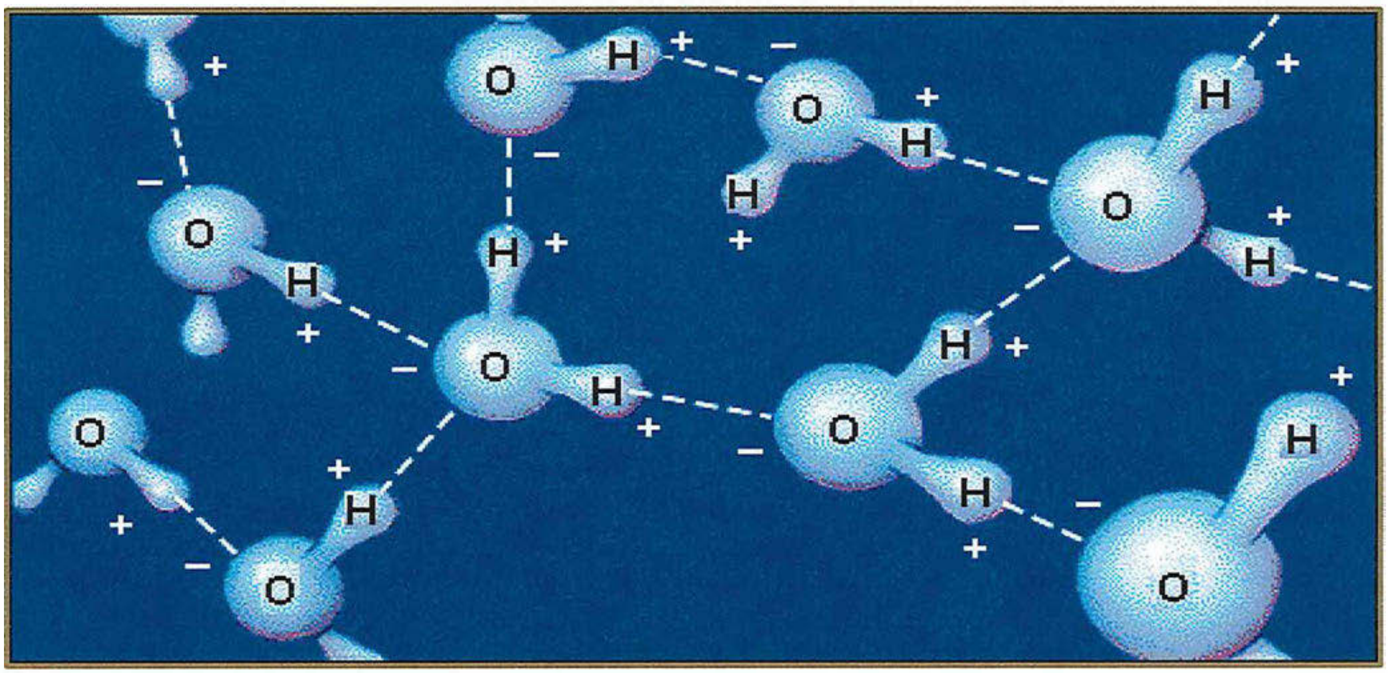




Structure and Properties of Water

Hydrogen bonding

- an oxygen atom in one water molecule exerts an attraction for a hydrogen atom in a neighboring molecule



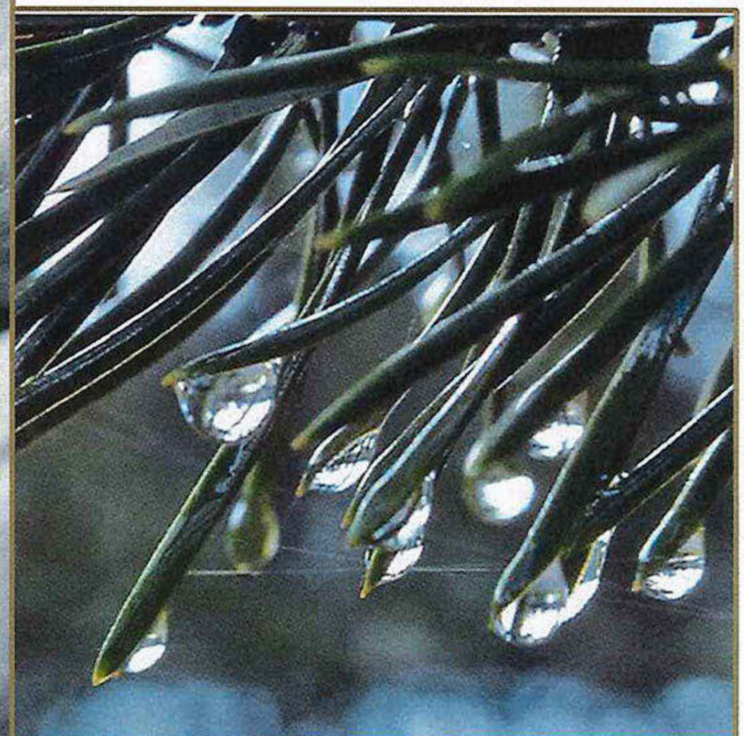
Structure and Properties of Water

Hydrogen bonding responsible for:

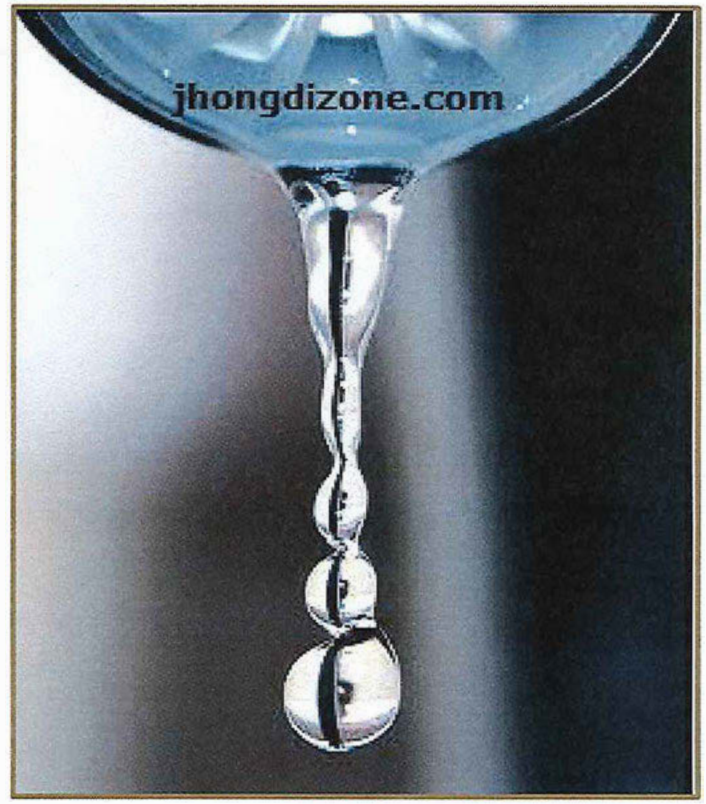
- Attraction of water molecules for each other
  - This attractive force known as ***cohesion***

- Attraction of water molecules for solid (negatively charged) surfaces
  - This attractive force known as ***adsorption*** or ***adhesion***

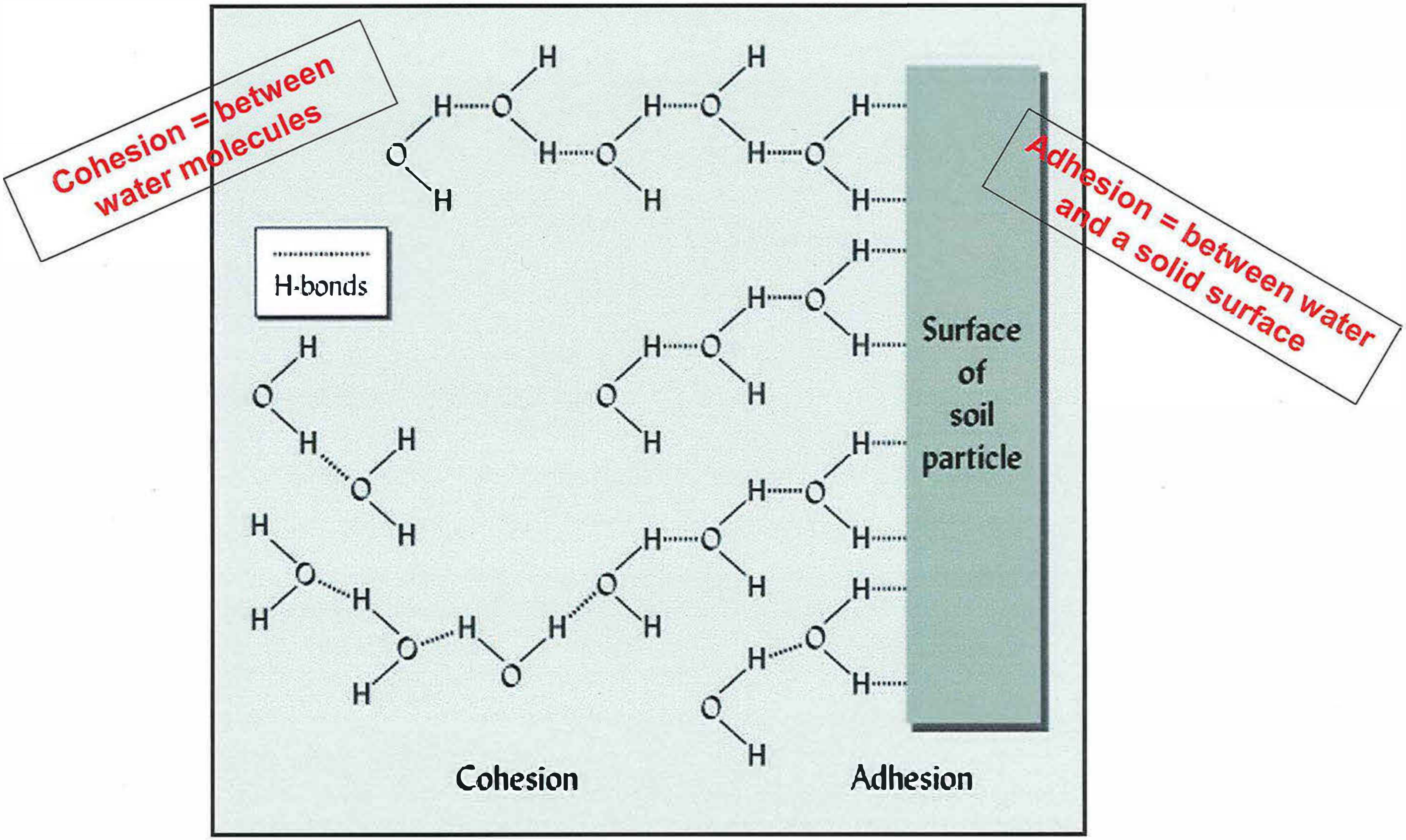
Forces of cohesion and adhesion illustrated



Forces of cohesion and adhesion illustrated



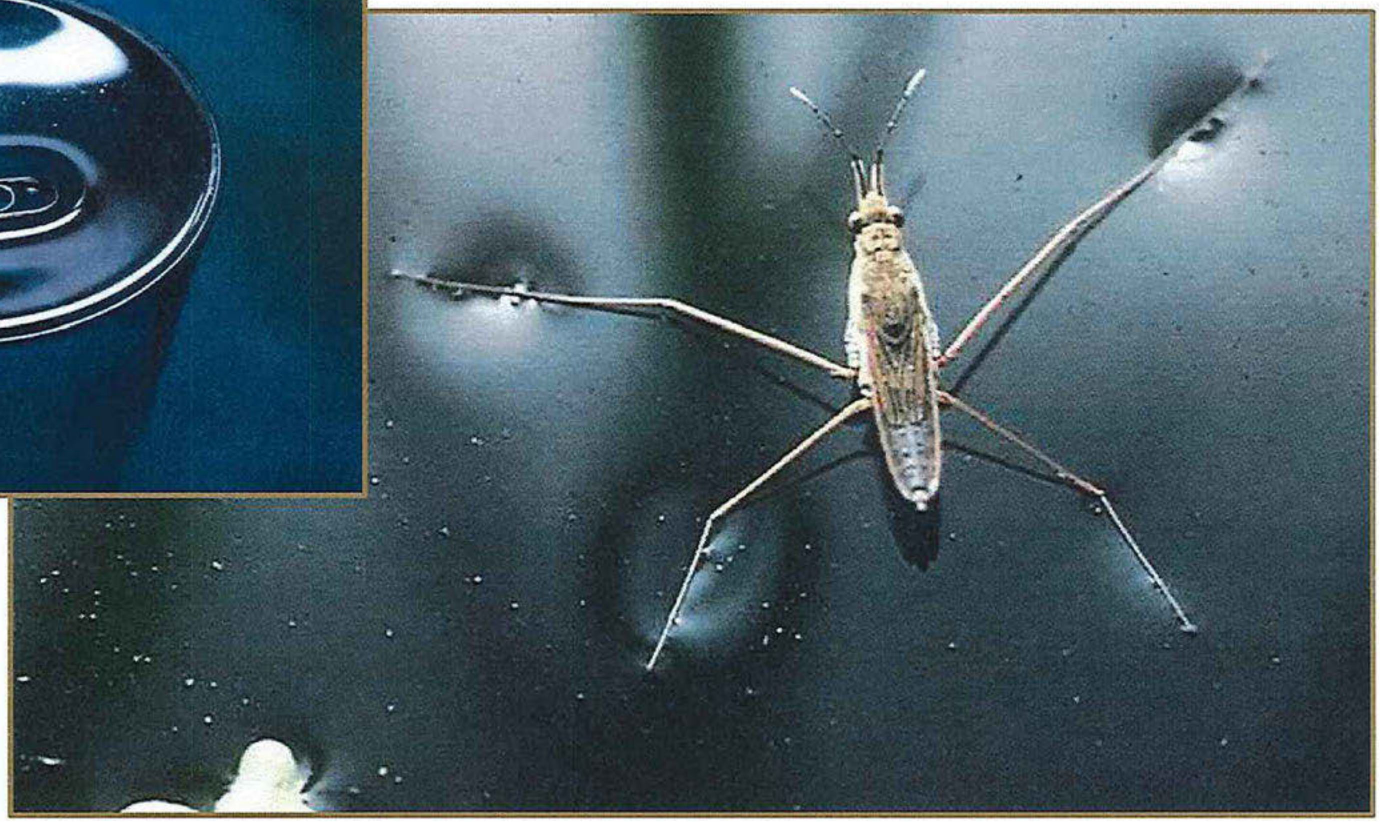
Forces of cohesion and adhesion



Structure and Properties of Water

- Surface Tension
  - Observed at liquid-air interface
  - Result of greater attraction of water molecules for each other (cohesion) than for air above
    - Net effect is inward force at water surface
    - Surface tension important in phenomenon of *capillarity* or *capillary action*

Surface tension



Capillary Action

- Liquids, (like water), will rise and be maintained in small tubes, above their normal surface of repose
- Water pulled up into tube by ***adhesion*** to the inner surface of tube, and by ***cohesion*** which pulls more water molecules along
- When weight of water becomes too heavy, gravity prevents water from rising any further in the tube

Capillary Action

- Height of rise inversely proportional to:
  - Tube radius (r)
  - Density of liquid
- Height of rise directly proportional to:
  - Surface tension of liquid (cohesion)
  - Attraction of liquid to surface (adhesion)

Capillary Action

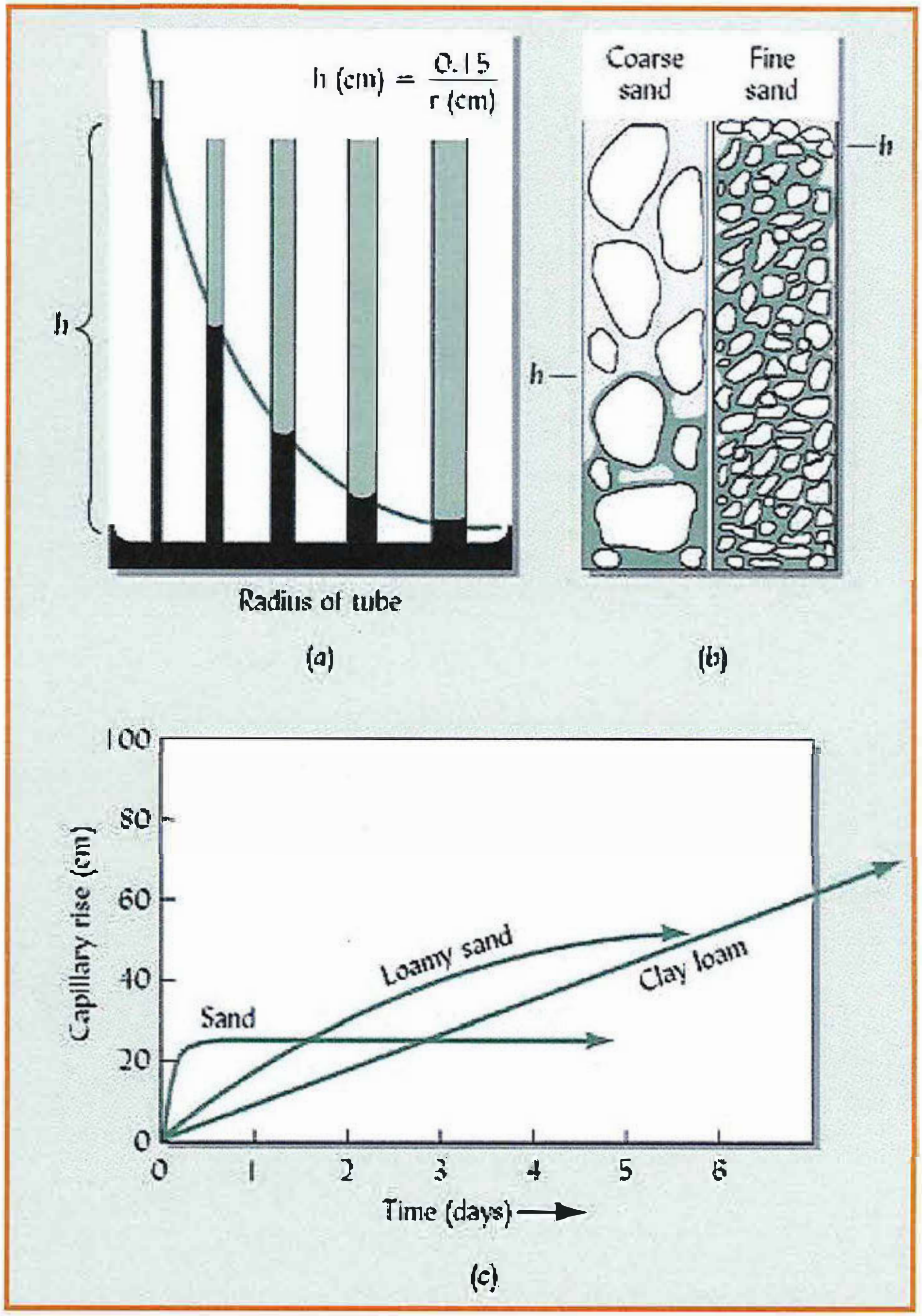
- The following equation can be used to calculate the height (h) of rise:

$$h(cm) = \frac{0.15\ (cm^2)}{r\ (cm)}$$

- The equation tells us that the smaller the tube's bore, the greater the capillary force and the higher the water will rise in the tube

Soil capillarity

The finer the soil texture, the greater the proportion of small-sized pores, and hence the higher the rise of water above a free water table.



Capillary Action

- Some tubes are small enough to retain water even after removal from the source
  - Requires external energy to remove water from these tubes
  - More external energy required as tube diameter decreases
- Soil pores analogous to capillary tubes
  - Water will move (rise) in soil against the force of gravity

Soil Water Energy Concepts

- Water (and all other substances) tend to move or change from a **higher** to a **lower** energy state (level)
  - Knowing energy levels at various points in the soil allows one to predict the **direction** of water movement in soil
  - **Differences** in energy levels from one point to another influence water movement

Forces Affecting Potential Energy

Three forces affect energy level of soil water

1. Adhesion (attraction of water to soil solids)
   - Provides matric force (responsible for adsorption and capillarity)
   - Reduces energy of water near particle surfaces

Forces Affecting Potential Energy

2. Attraction of water to ions and other solutes results in osmotic forces
   - For example: water moving from the soil into a root
   - Pure water moving across a semi-permeable membrane into a solution is evidence of osmotic force
     - Reduces the energy state of water in the soil solution

Forces Affecting Potential Energy

3. Force of gravity which always pulls water downward
   - Energy level of water at a given elevation (or height) is always higher than that of water at a lower elevation (or height) in a soil

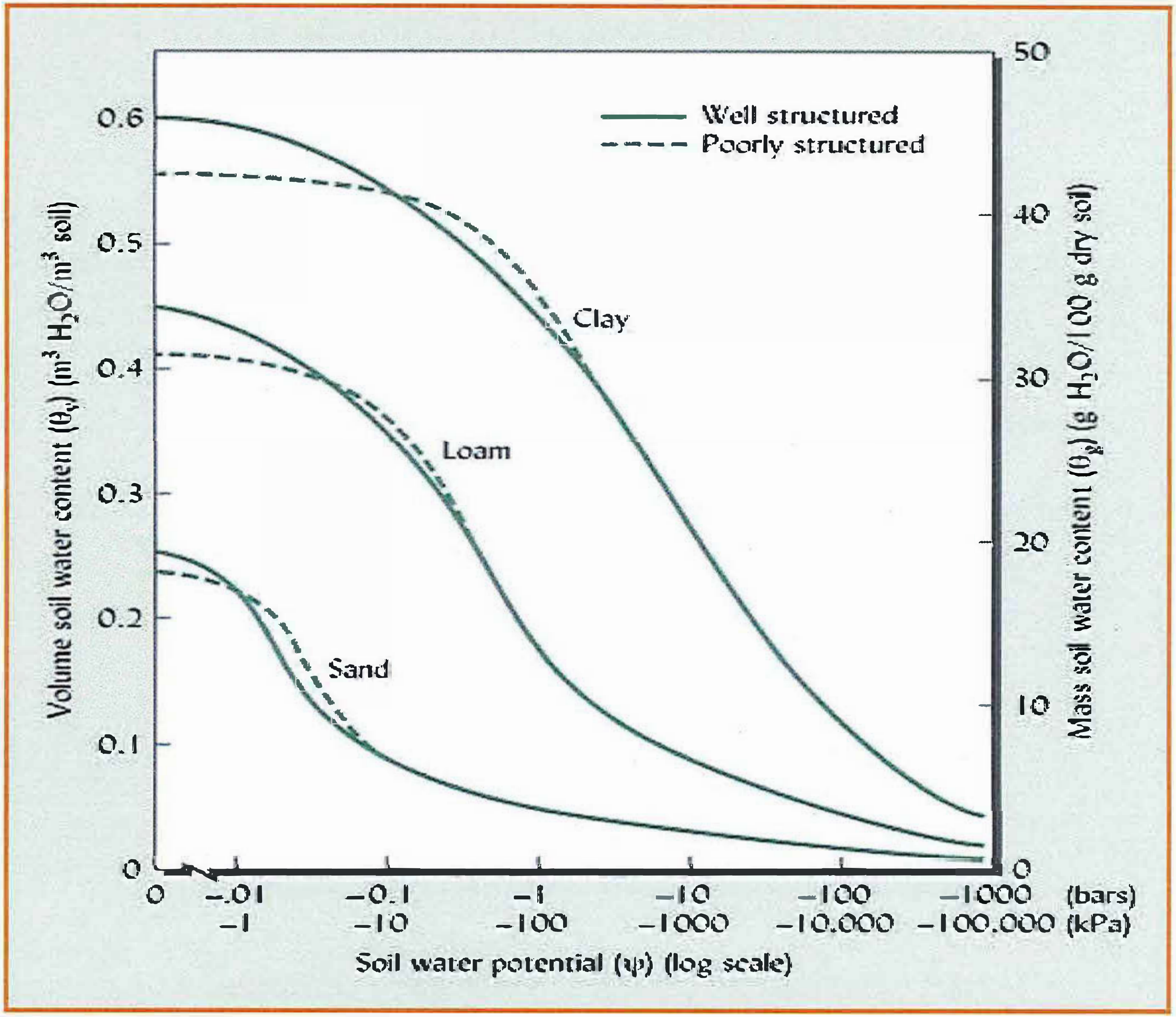
Soil Water Potential

The difference in energy level of water from one site to another or one condition to another determines rate and direction of water movement in soils and plants

- Wet soil to dry soil = high energy to low energy potential
- Water will move spontaneously from wet soil to dry soil

Soil water potential curves

Clay soils hold more water at a given potential than loam or sand; also clay holds water more tightly



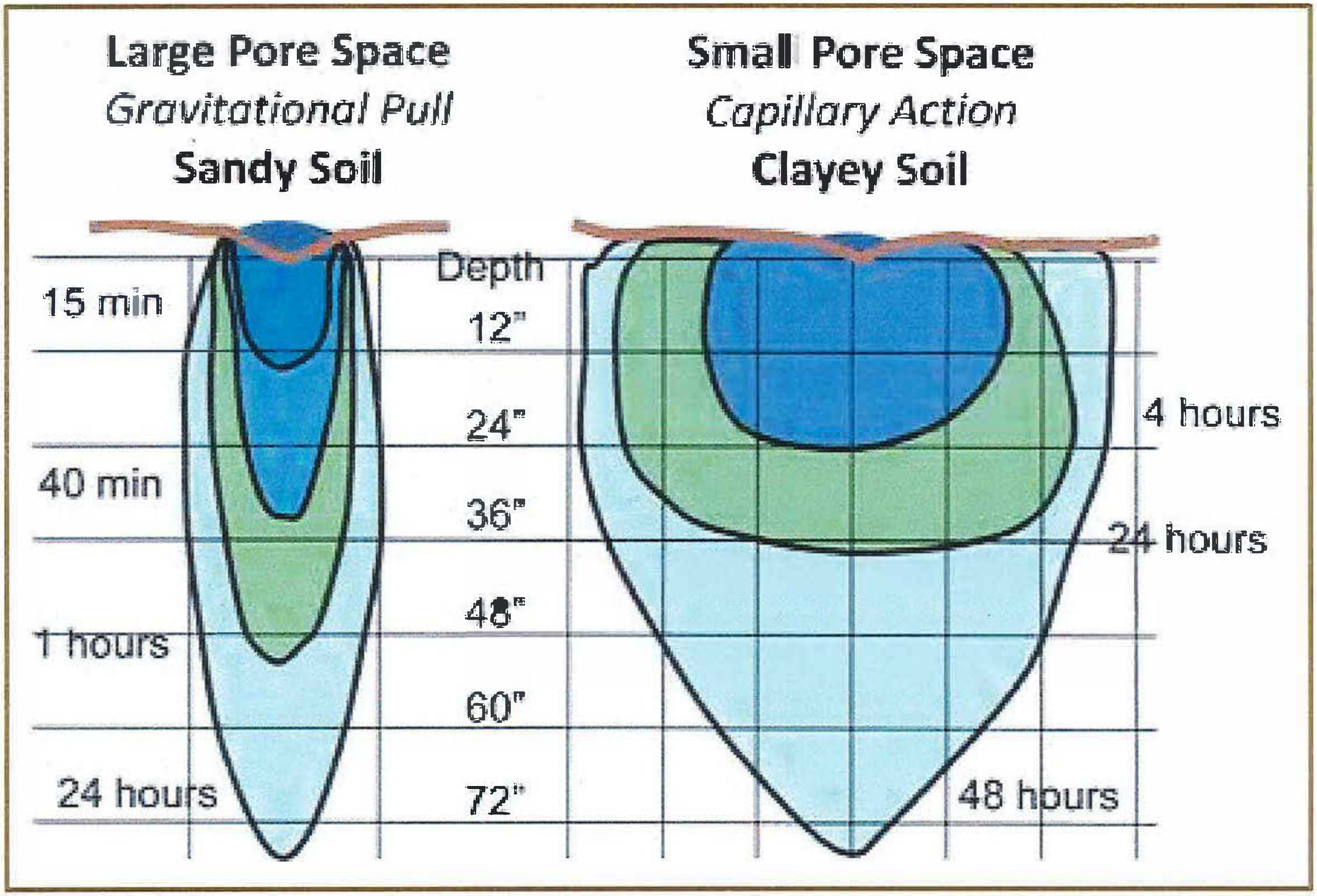
Measuring water Content

- Gravimetric: mass of water per given mass of soil (often 1 kg)
  - Wet basis: water per unit of wet soil
    - Natural condition
  - Dry basis: water per unit of dry soil
    - Prediction

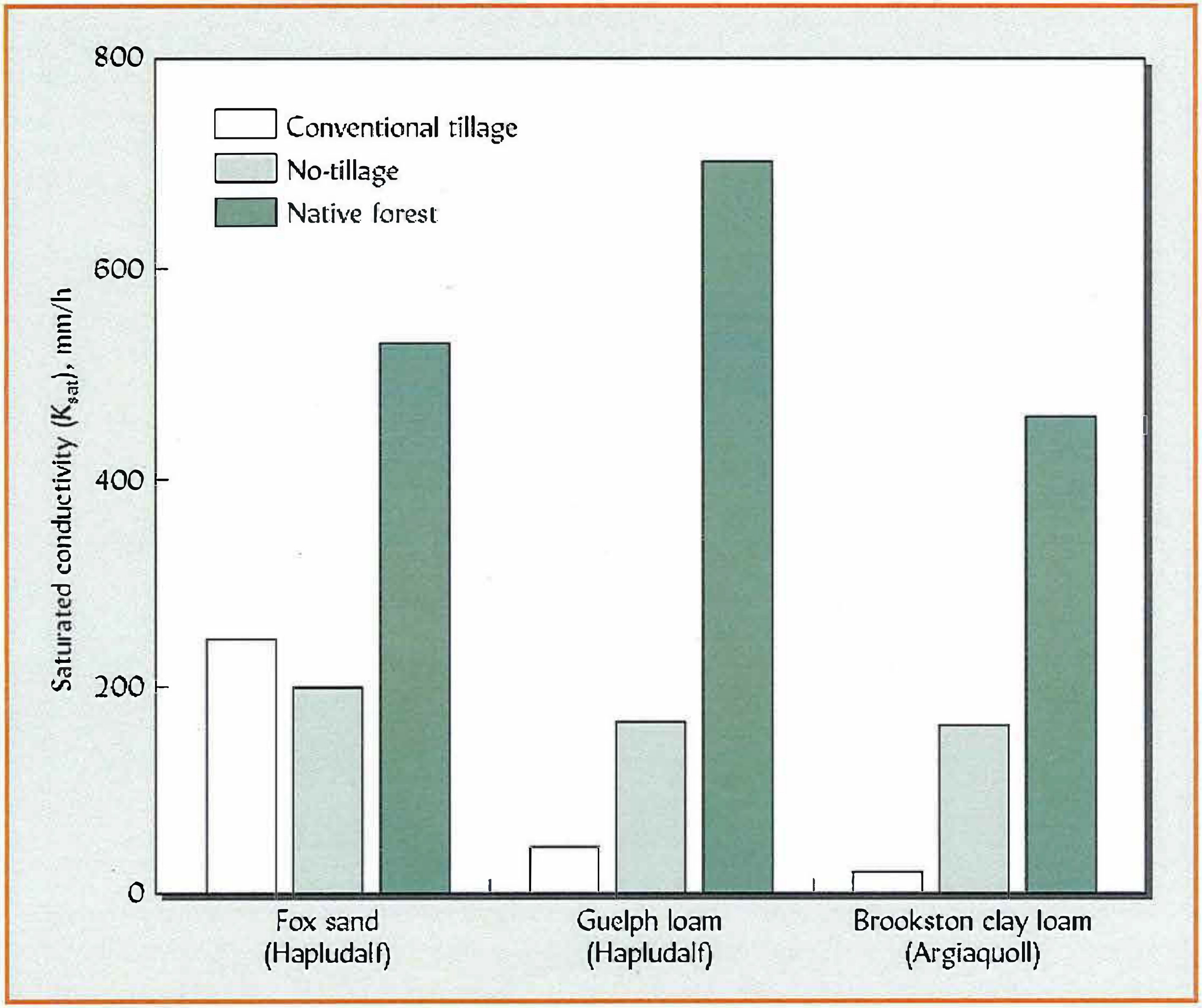
Measuring water Content

- Volumetric (θ): volume of water per given volume of soil (for example 1 cm^3 or $1 m^3$)
  - Applicable as a depth measurement
    - For example: depth of wetting after rain or irrigation

Rate of water movement in sandy vs clayey soils



Effect of land management and soil texture on saturated hydraulic conductivity (K_{sat})



Infiltration and Percolation

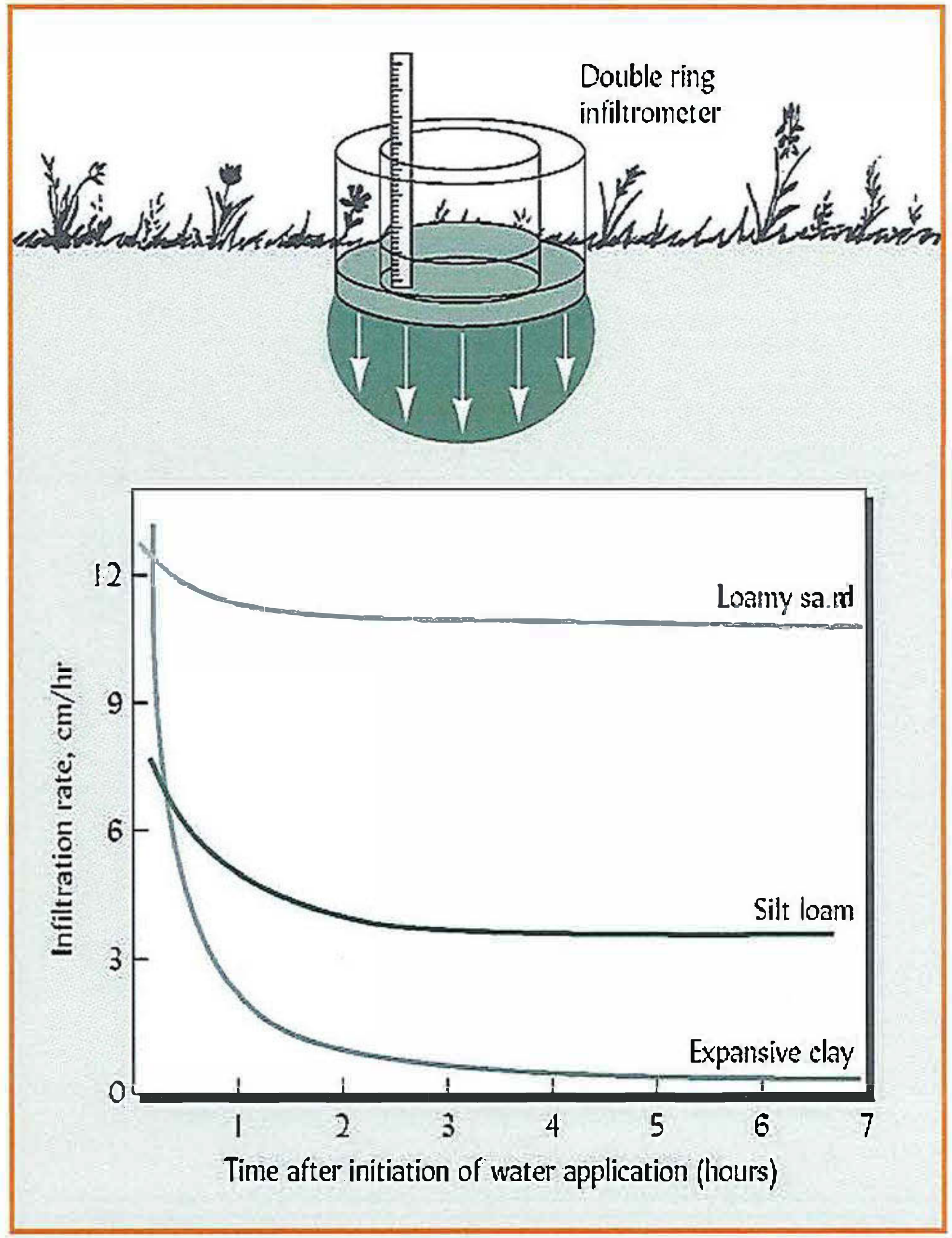
- Infiltration: initial movement of water into soil pores (at the soil surface)

- Percolation: subsequent movement of water through the soil profile
  - Function of both saturated flow and unsaturated flow
  - Depends on the hydraulic conductivity of the soil

Infiltration and Percolation

- Percolation
  - In dry soils is governed by saturated flow in upper layers with matric influence from drier areas
  - Strongly influenced by surface/subsurface texture
    - Crusting will reduce infiltration
      - Silty soils: rapid infiltration initially, structure deteriorates quickly causing a seal to form
    - Well aggregated soils show more constant rates
  - Long term infiltration depends on having enough room (storage) in soil for more water

Measuring infiltration capacity by double ring infiltrometer



Soil Water Classification

- Gravitational water
  - Water held in soils between 0 and –0.3 bars
  - Drains by gravity and somewhat available to plants
    - Most pores filled with water not air
  - Responsible for saturation of soils
  - Upper limit –0.3 bars, is called *field capacity*

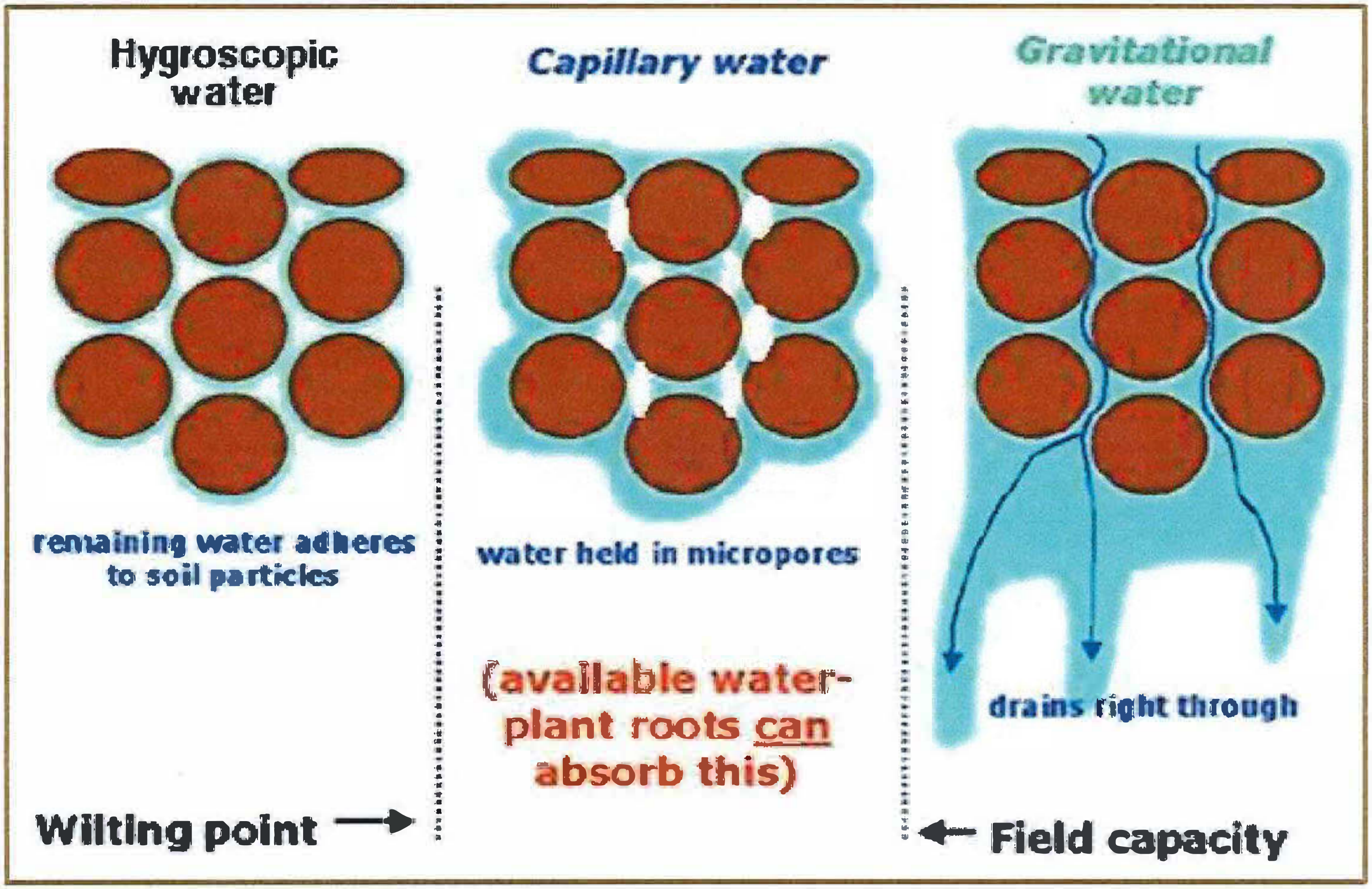
Soil Water Classification

- Capillary water
  - Water held in soils between 0 and –30 bars
  - Most important water source for plants
    - Plant available water held between 0 and –15 bars
  - Does not drain by gravity
  - Moves by matric and osmotic forces
  - *Permanent wilting point* at –15 bars
    - Point at which roots are unable to exert enough pressure to extract more water from soil pores

Soil Water Classification

- Hygroscopic water
  - Present whenever soil contains any water
  - Consists of water bound in films to surfaces of particles
    - Water films often only a few molecules thick
  - Water is bound at tensions (pressures) of greater than –31 bars
  - *Hygroscopic coefficient* at –31 bars

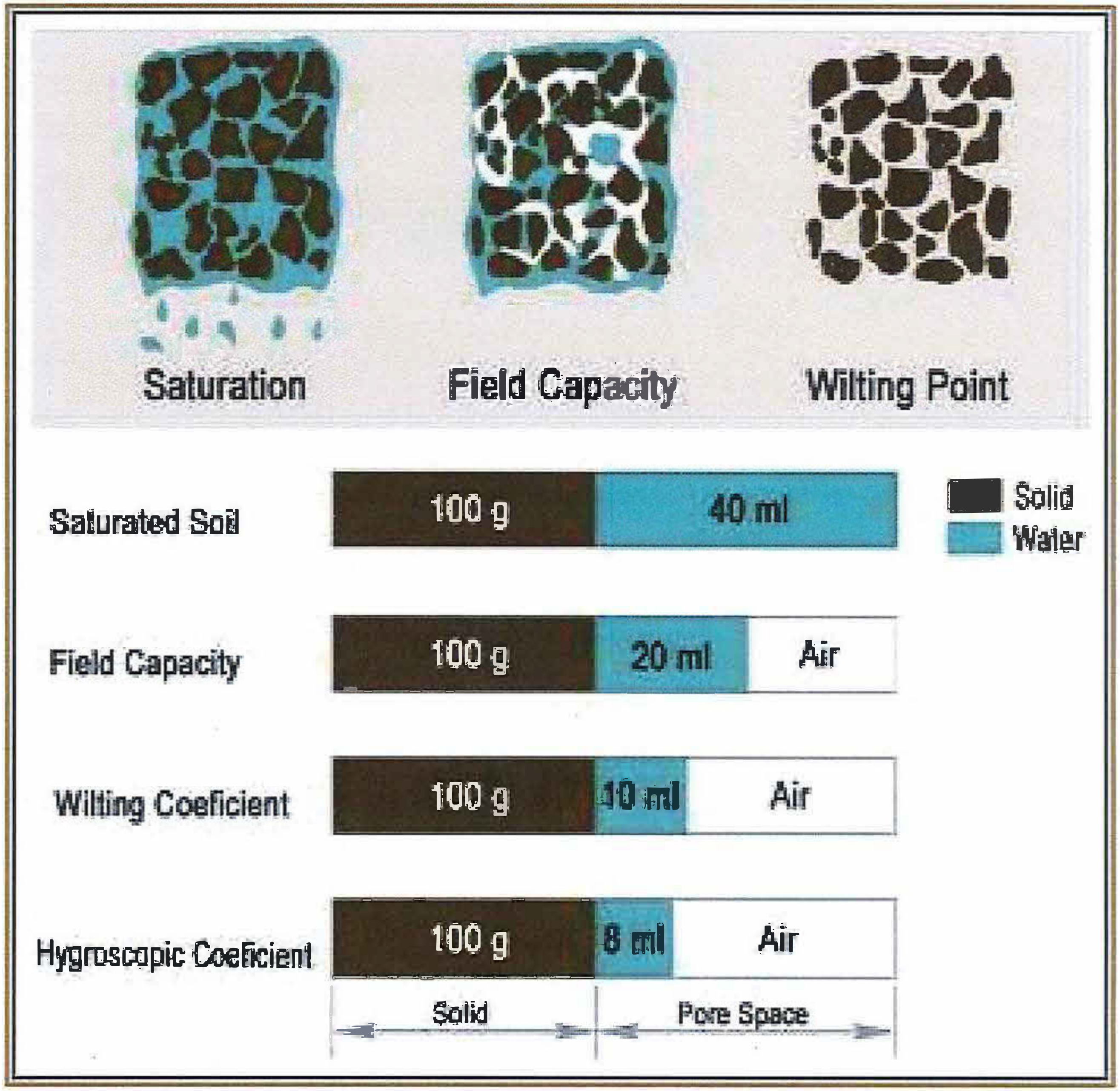
SOIL WATER CLASSIFICATION



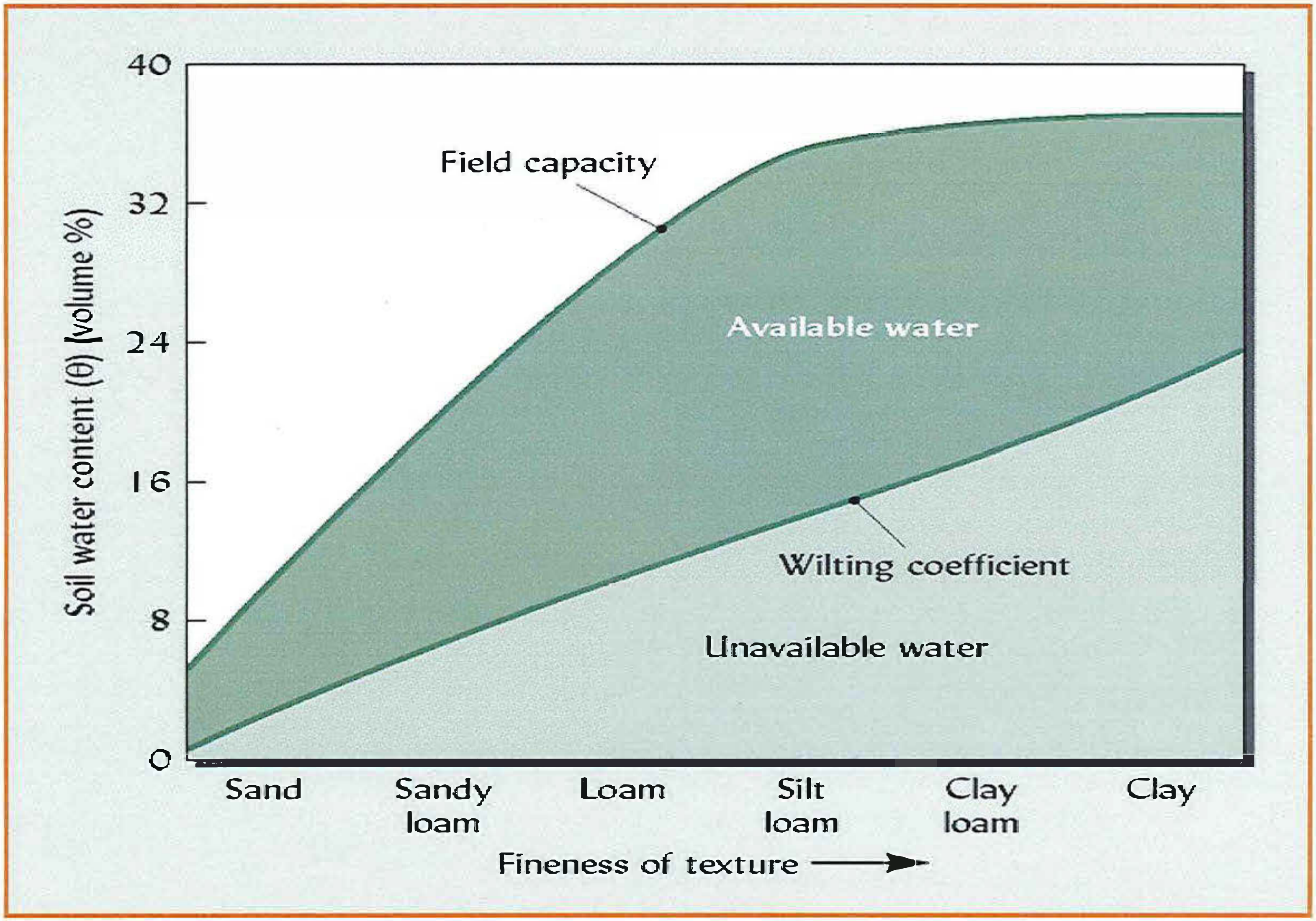
Soil Water

- Very difficult to remove all water from soil
  - Requires very high, extended periods of heat
- Texture affects the proportion of water which is actually plant available
  - Clays contain more water than loams but a higher percentage is hygroscopic

Volumes of water and air associated with a 100 g slice of soil solids in a well granulated silt loam at different moisture levels

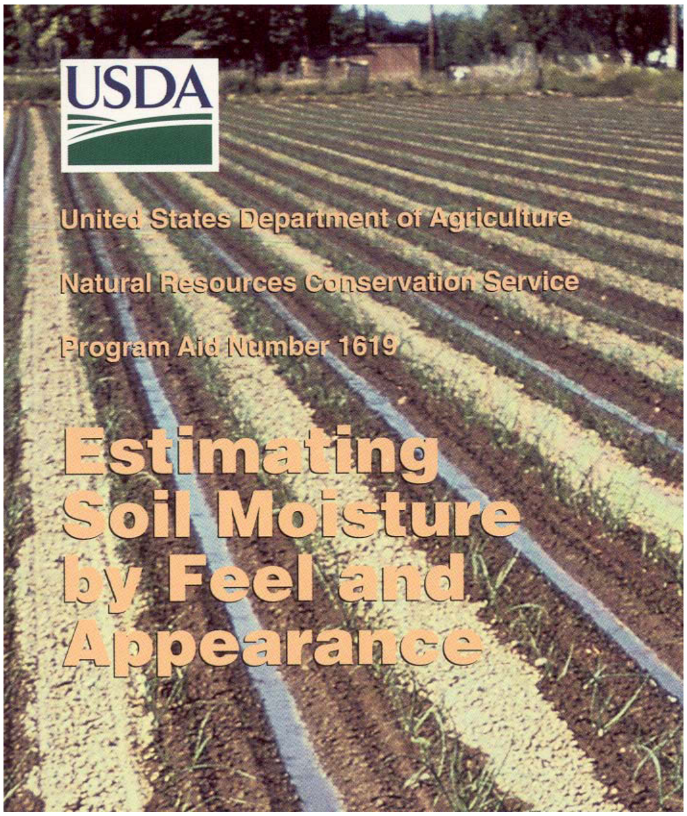


General relationship between soil water characteristics and soil texture



Estimating Soil Moisture by Feel and Appearance

Irrigation Water Management (IWM) is applying water according to crop needs in an amount that can be stored in the plant root zone of the soil.



The "feel and appearance method" is one of several irrigation scheduling methods used in IWM. It is a way of monitoring soil moisture to determine when to irrigate and how much water to apply. Applying too much water causes excessive runoff and/or deep percolation. As a result, valuable water is lost along with nutrients and chemicals, which may leach into the ground water.

The feel and appearance of soil vary with texture and moisture content. Soil moisture conditions can be estimated, with experience, to an accuracy of about 5 percent. Soil moisture is typically sampled in I-foot increments to the root depth of the crop at three or more sites per field. It is best to vary the number of sample sites and depths according to crop, field size, soil texture, and soil stratification. For each sample the "feel and appearance method" involves:

1. Obtaining a soil sample at the selected depth using a probe, auger, or shovel;
2. Squeezing the soil sample firmly in your hand several times to form an irregularly shaped "ball";
3. Squeezing the soil sample out of your hand between thumb and forefinger to form a ribbon;
4. Observing soil texture, ability to ribbon, firmness and surface roughness of ball, water glistening, loose soil particles, soil/water staining on fingers, and soil color. [Note: A very weak ball will disintegrate with one bounce of the hand. A weak ball disintegrates with two to three bounces;
5. Comparing observations with photographs and/or charts to estimate percent water available and the inches depleted below field capacity.

Example:

Sample Depth	Zone	USDA Texture	AWC*for Zone	Soil Moisture Delpetion**	Percent Depletion
6”	0-12"	sandy loam	1.4"	1.0"	70
18"	12-24"	sandy loam	1.4"	.8"	55
30"	24-36"	loam	2.0"	.8"	40
42"	36-48"	loam	2.0"	.5"	25
			6.8"	3.1"	

Result: A 3.1" net irrigation will refill the root zone.
** Available Water Capacity*
*** Determined by “feel and appearance method”*

Available Water Capacity (AWC) is the portion of water in a soil that can be readily absorbed by plant roots of most crops.

Soil Moisture Deficit (SMD) or Depletion is the amount of water required to raise the soil-water content of the crop root zone to field capacity.

Appearance of fine sand and loamy fine sand soils at various soil moisture conditions.

Available Water Capacity 0.6-1.2 inches/foot

Percent Available: Currently available soil moisture as a percent of available water capacity.

In/ft. Depleted: Inches of water currently needed to refill a foot of soil to field capacity.

0-25 percent available
1.2-0.5 in./ft. depleted

Dry, loose, will hold together if not disturbed, loose sand grains on fingers with applied pressure. (Not pictured)

25-50 percent available
0.9-0.3 in./ft. depleted

Slightly moist, forms a very weak ball with well-defined finger mark

50-75 percent available
0.6-0.2 in./ft. depleted

Moist, forms a weak ball with loose and aggregated sand grains on fingers, darkened color, moderate water staining on fingers, will not ribbon.

75-100 percent available
0.3-0.0 in./ft. depleted

Wet, forms a weak ball, loose and aggregated sand grains remain on fingers, darkened color, heavy water staining on fingers, will not ribbon

100 percent available
0.0 in./ft. depleted (field capacity)

Wet, forms a weak ball, moderate to heavy soil/ water coating on fingers, wet outline of soft ball remains on hand. (Not pictured)

Appearance of sandy loam and fine sandy loam soils at various soil moisture conditions.

Available WaterCapacity 1.3-1.7 inches/foot

Percent Available: Currently available soil moisture as a percent of available water capacity.

In/ft. Depleted: Inches of water currently needed to refill a foot of soil to field capacity.

0-25 percent available 1 7-1.0 in/ft. depleted

Dry, forms a very weak ball, aggregated soil grains break away easily from ball. (Not pictured)

25-50 percent available 1.3-0.7 in/ft. depleted

Slightly moist, forms a weak ball with defined finger marks, darkened color, no water staining on fingers, grains break away.

50-75 percent available 0.9-0.3 in./ft. depleted

Moist, forms a ball with defined finger marks, very light soil/water staining on fmgers, darkened color, will not slick.

75-100 percent available 0.4-0.0 in./ft. depleted

Wet, forms a ball with wet outline left on hand, light to medium staining on fingers, makes a weak ribbon between the thumb and forefinger.

100 percent available 0.0 in./ft. depleted (field capacity)

Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy soil/water coating on fingers. (Not pictured)

Appearance of sandy clay loam, loam, and silt loam soils at various soil moisture conditions.

Available WaterCapacity 1.5-2.1 inches/foot

Percent Available: Currently available soil moisture as a percent of available water capacity.

In/ft. Depleted: Inches of water currently needed to refill a foot of soil to field capacity.

0-25 percent available
2.1-1.1 in./ft. depleted

Dry, soil aggregations break away easily, no staining on fingers, clods crumble with applied pressure. (Not pictured)

25-50 percent available
1.6-0.8 in./ft. depleted

Slightly moist, forms a weak ball with rough surfaces, no water staining on fingers, few aggregated soil grains break away.

50-75 percent available
1.1-0.4 in./ft. depleted

Moist, forms a ball, very light staining on fingers, darkened color, pliable, forms a weak ribbon between the thumb and forefinger.

75-100 percent available
0.5-0.0 in/ft. depleted

Wet, forms a ball with well-defined finger marks, light to heavy soil/water coating on fingers, ribbons between thumb and forefinger.

100 percent available
0.0 in/ft. depleted (field capacity)

Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy soil/water coating on fingers. (Not pictured)

Appearance of clay, clay loam, and silt clay loam soils at various soil moisture conditions.

Available WaterCapacity 1.6-2.4 inches/foot

Percent Available: Currently available soil moisture as a percent of available water capacity.

In/ft. Depleted: Inches of water currently needed to refill a foot of soil to field capacity.

0-25 percent available 2.4-1.2 in/ft. depleted

Dry, soil aggregations separate easily, clods are hard to crumble with applied pressure. (Not pictured)

25-50 percent available 1.8-0.8 in/ft. depleted

Slightly moist, forms a weak ball, very few soil aggregations break away, no water stains, clods flatten with applied pressure.

50 - 75 percent available 1.2-0.4 in./ft. depleted

Moist, forms a smooth ball with defined finger marks, light soil/water staining on fingers, ribbons between thumb and forefinger.

75-100 percent available 0.6-0.0 in./ft. depleted

Wet, forms a ball, uneven medium to heavy soil/water coating on fingers, ribbons easily between thumb and forefinger.

100 percent available 0.0 in./ft. depleted (field capacity)

Wet, forms a soft ball, free water appears on soil surface after squeezing or shaking, thick soil/water coating on fingers, slick and sticky. (Not pictured)

Guidelines for Estimating Soil Moisture Conditions

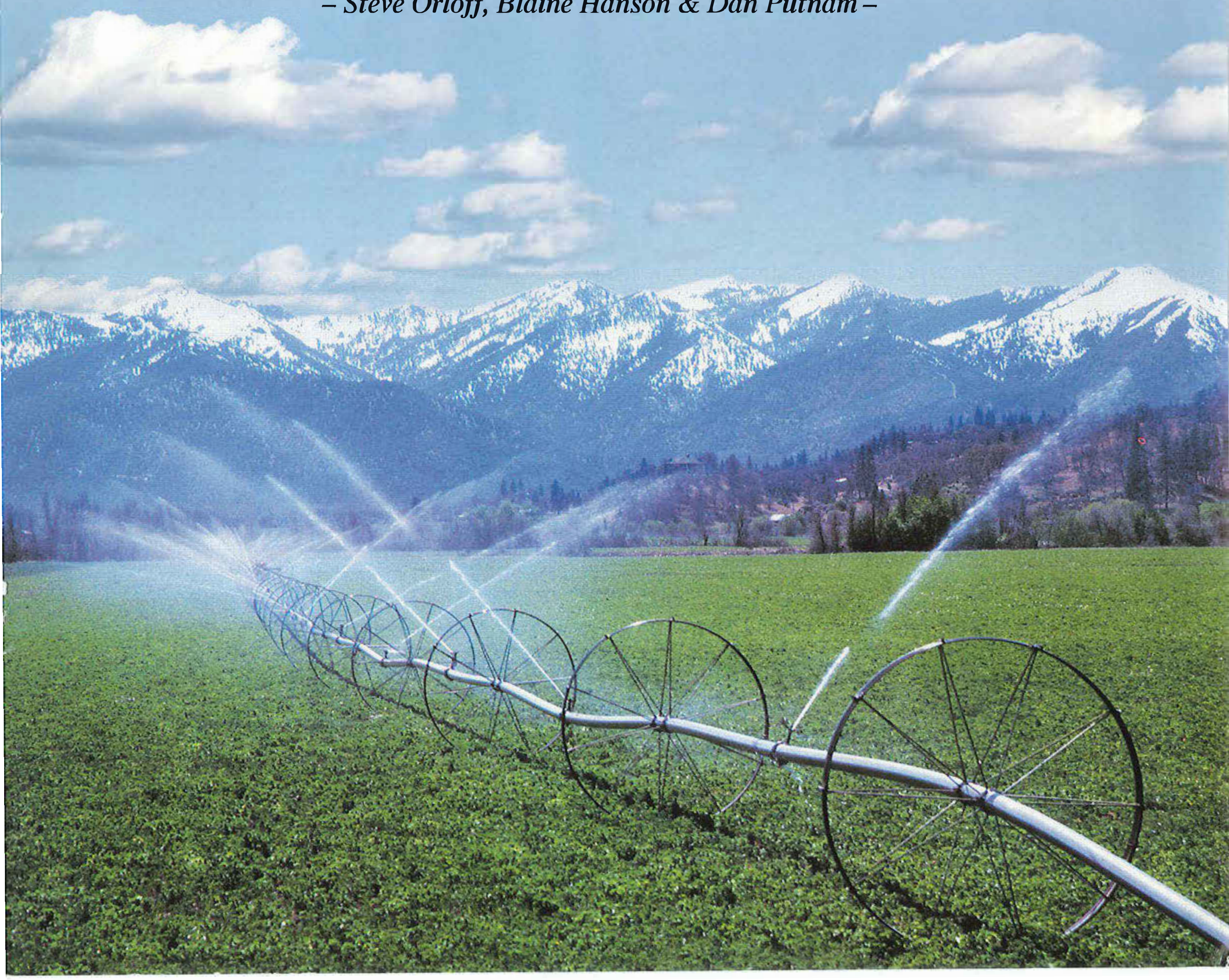
	Coarse Texture- Fine Sand and Loamy Fine Sand	Moderately Coarse Texture Sandy Loam and Fine Sandy Loam	Medium Texture - Sandy Clay Loam, Loam, and Silt Loam	Fine Texture- Clay, Clay Loam, or Silty Clay Loam
	Available Water Capacity (Inches/Foot)			
	0.6-1.2	1.3-1.7	1.5-2.1	1.6-2.4
Available Soil Moisture Percent	Soil Moisture Deficit (SMD) in inches per foot when the feel and appearance of the soil are as described.			
0-25	Dry, loose, will hold together if not disturbed, loose sand grains on fingers with applied pressure. SMD 1.2-0.5	Dry, forms a very weak ball, aggregated soil grains break away easily from ball. SMD 1.7 -1.0	Dry. Soil aggregations break away easily. no moisture staining on fingers, clods crumble with applied pressure. SMD 2.1-1.1	Dry, soil aggregations easily separate, clods are hard to crumble with applied pressure SMD 2.4-1.2
25-50	Slightly moist, forms a very weak ball with well-defined finger marks, light coating of loose and aggregated sand grains remain on fingers. SMD O.9-0.3	Slightly moist, forms a weak ball with defined finger marks, darkened color, no water staining on fingers, grains break away. SMD 1.3-0.7	Slightly moist, forms a weak ball with rough surfaces, no water staining on fingers, few aggregated soil grains break away. SMD1.6-0.8	Slightly moist, forms a weak ball, very few soil aggrega-tions break away, no water stains, clods flatten with applied pressure SMD 1.8-0.8
50-75	Moist, forms a weak ball with loose and aggregated sand grains on fingers, darkened color, moderate water staining on fingers, will not ribbon. SMD O.6-0.2	Moist, forms a ball with defined finger marks. very light soil/water staining on fingers. darkened color, will not slick. SMD O.9-0.3	Moist, forms a ball, very light water staining on fingers, darkened color, pliable, forms a weak ribbon between thumb and forefinger. SMD 1.1- 0.4	Moist. forms a smooth ball with defined finger marks, light soil/water staining on fingers, ribbons between thumb and forefinger. SMD I.2-0.4
75-100	Wet, forms a weak ball, loose and aggregated sand grains remain on fingers, darkened color, heavy water staining on fingers, will not ribbon. SMD O.3-0.0	Wet, forms a ball with wet outline left on hand, light to medium water staining on fingers, makes a weak ribbon between thumb and forefinger. SMD O.4-0.0	Wet, forms a ball with well defined finger marks, light to heavy soil/water coating on fingers, ribbons between , thumb and forefinger. SMD O.5 -0.0	Wet, forms a ball, uneven medium to heavy soil/water coating on fingers, ribbons easily between thumb and forefinger. SMD O.6-0.0
Field Capacity (100 %)	Wet, forms a weak ball, moderate to heavy soil/ water coating on fingers, wet outline of soft ball remains on hand. SMD 0.0	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking,medium to heavy soil/water coating on fingers. SMD 0.0	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy soil/water coating on fingers. SMD 0.0	Wet, forms a soft ball, free water appears on soil surface after squeezing or shaking, thick soil/water coating on fingers, slick and sticky. SMD 0.0

April 1998

Soil-Moisture Monitoring

A Simple Method to Improve Alfalfa and Pasture Irrigation Management

– *Steve Orloff, Blaine Hanson & Dan Putnam* –



Introduction

Irrigation water is essential for profitable crop production in most of the arid West. Proper irrigation management is key for high yields and to avoid stress from too much or too little water. Improper irrigation management limits yields more often and to a greater degree than any other production factor. Perhaps the reason why irrigation practices often fall short of optimum is that nearly all the action occurs in the soil out of our view.

Determining when to irrigate and how much water to apply are not simple tasks. How can you assess whether irrigation practices are correct? This publication provides information on a relatively simple and effective method for managing irrigation on alfalfa and irrigated pasture.

Funding provided by:
U.S. Department of the Interior, Fish and Wildlife Service under the authority of the Klamath Act and Klamath River Basin Conservation Area Restoration Program, administered and implemented by: The Siskiyou Resource Conservation District.

In cooperation with:
University of California Cooperative Extension
Scott River Watershed Council

Published by:
University of California Cooperative Extension, Siskiyou County
1655 S. Main Street, Yreka, California 96097

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Additional Information:
For additional information and an Excel Spreadsheet to graph data see:
http://alfalfa.ucdavis.edu.

What's the Best Strategy for Irrigation Scheduling?

The decision of when to irrigate is usually based on past experiences, weather-based information (crop evapotranspiration data), or soil-based measurements. Past experiences may not be correct and are often not adjusted for annual changes in weather.

Scheduling irrigations based on crop evapotranspiration can be difficult because, unlike other crops with a single harvest per season, the multiple harvests of alfalfa and pasture confound the process. Irrigation water cannot be applied too close to a cutting, and fields obviously cannot be irrigated while the crop is curing. Therefore, there is typically a 6- to even 20-day period during which fields cannot be irrigated. This can make irrigation scheduling using weather-based information problematic. In addition, it may be difficult to obtain accurate data for some locations and, even when data are available, the task of keeping track of evapotranspiration data for individual fields can be time consuming. Because of the difficulties and shortcomings of these methods, soil-based irrigation scheduling may be the preferred technique.

Soil-based measurements may be far more practical and easy-to-use for alfalfa and pasture producers. Soil moisture content often goes unchecked. If soil moisture is monitored, it is usually only done using a shovel or soil auger. While better than nothing, using a shovel or auger is imprecise and is only useful for a gross evaluation of the soil moisture content in the upper foot, or less, of soil. Several inexpensive technologies may help growers monitor soil moisture.

To simplify information, trade names of products have been used. No endorsement of named products is intended, nor is criticism implied of similar products that are not mentioned.

Expressing Soil Moisture Content

Soil moisture levels can be expressed in different ways, depending largely on the instrument used. Soil moisture content is often expressed as a percent (the weight of the water in the soil divided by the weight of oven-dry soil x 100). Other soil moisture monitoring devices use soil moisture tension to indicate soil moisture levels. Soil moisture tension refers to how strongly water is held on soil particles—the higher the tension the more difficult it is for plant roots to extract water from the soil. Therefore, low soil moisture tension indicates moist soil and high soil moisture tension indicates dry soil. Soil moisture tension is usually expressed in centibars. For some types of soil moisture resistance blocks, the instrument readings must be converted to soil moisture tension using appropriate calibration relationships.

Resistance Blocks – A Useful Tool

More than six years of field studies in the Scott Valley (a high-elevation valley in northern California) demonstrated the usefulness of soil moisture monitoring in alfalfa and irrigated pasture fields. These studies showed that significant improvements in irrigation management were possible in many fields by monitoring soil moisture levels and adjusting irrigation practices accordingly. Electrical resistance blocks provided a reliable indication of soil moisture levels and are a cost-effective tool for effective irrigation management.

Ask Questions About Water Management!

➤ When do I start irrigating?

This is often a difficult decision. The soil profile is often filled from winter rains. But after the crop resumes growth in spring and the weather warms, you must decide when the soil moisture is depleted enough to require irrigation. Most irrigation systems do not have the capacity to "catch up" when the soil profile has been excessively depleted in spring.

Answer: *The first irrigation should occur when soil moisture tension reaches the recommended value for your soil type (see table on next page).*

➤ Do I irrigate again before harvest?

Alfalfa is most sensitive to water stress after cutting when the plants start to regrow. Resistance block readings help assess whether the soil-moisture content is sufficient to avoid water stress through the duration of the harvest period until irrigation can be resumed.

Answer: *Track soil moisture to predict the rate of soil moisture depletion. By graphing the data and extending the line through the harvest period, you can anticipate soil moisture loss during harvest. If anticipated soil moisture levels fall well below the recommended values for your soil type (see table on next page), an irrigation or partial irrigation may be desirable before cutting.*

➤ Did I fill the profile?

Soil moisture sensors are very useful to assess the moisture status at the lower end of the root zone—especially for a deep-rooted crop like alfalfa. The lower half of the root zone supplies moisture reserves to draw upon when needed and should not be excessively depleted.

Answer: *If the soil profile is filled after irrigation, soil moisture readings at all depths should return to less than 10 centibars for a sandy soil and less than about 30 centibars for medium/fine-textured soil. If the sensors do not respond after irrigation the water did not penetrate to the depth of the sensor. Monitor soil moisture after each irrigation to determine how many irrigations are needed to refill the profile.*

➤ Should I change my irrigation practices?

Soil moisture monitoring is helpful to verify that current irrigation practices satisfy, but do not exceed, the needs of the crop. A graph of soil moisture readings over the season provides a sound basis for altering and fine-tuning irrigation practices.

Answer: *Plot soil moisture readings on a graph (see example graphs on page 5). The lines on your graph should oscillate as they do in Figure 1. The highest soil moisture tension reached should be the values where irrigation is recommended (see table on next page). Then, following irrigations, the values should return to less than 10 for a sandy soil and less than about 30 for a medium/fine-textured soil. If values exceed the recommended range, the soil is becoming excessively dry between irrigations and the field should be irrigated more frequently or with more water per irrigation. If values are low (indicating adequate moisture), irrigation can be skipped or delayed until soil moisture sensors indicate irrigation is needed.*

Using Soil Moisture Data

Resistance Blocks

Electrical resistance blocks (also called gypsum blocks or resistance blocks) are not new, but recent advances have improved their accuracy and ease-of-use. Resistance blocks evaluate soil moisture tension by measuring the electrical resistance between two electrodes. The blocks take up and release moisture as the soil wets and dries. The higher the water content of the blocks, the lower the electrical resistance. The electrical resistance is measured with a portable meter that is connected to wire leads coming from the moisture sensors (Figure 4). Because there is a known and consistent calibration between electrical resistance and soil moisture for the Watermark® block (a resistance block made by Irrometer Company, Inc.), it can closely estimate soil moisture tension in centibars.

Interpreting the resistance block readings

An important point to understand when using the Watermark® sensors is that *the lower the reading the higher the soil moisture content*, and conversely, *the higher the reading the lower the moisture content.* When the soil is saturated after a rainfall or irrigation (air spaces are mostly filled with water) the Watermark® reading is low, typically less than 5 to 10 centibars. As evaporation from the soil surface and transpiration by the crop dry the soil, the moisture sensor readings gradually increase until they indicate need for an irrigation.

The centibar reading at which irrigation is necessary depends on soil type (see table). Sandy soils retain far less water than soils with a high clay or organic matter content, so irrigation on sandy soils should occur more frequently and at a lower soil moisture tension value. Soil moisture sensors may not be useful for very sandy soils with extremely low water holding capacity, as the sensors might not respond quickly enough to the rapid decline in soil moisture.

After the field is irrigated the centibar readings typically return to the teens or single digit values. These wetting and drying cycles continue throughout the season as the crop is irrigated and then the soil dries with crop water use. The key to proper irrigation management using soil moisture sensors is to monitor the sensors regularly, track the soil moisture level, and irrigate when the centibar readings are in the desired range for your soil type (See Figure 1). Irrigating when the soil moisture readings exceed the desired range may result in crop stress and yield loss. Irrigation before the readings reach the desired range may result in excessive irrigation, water wastage or runoff.

Using and interpreting a soil-moisture graph

The best way to use the soil-moisture measurements is to plot them on a graph. The plotted data present a picture of the soil moisture status and indicate how fast the soil is drying. After a few points are plotted, you can estimate approximately how many days it will take for the soil to dry before irrigation is needed. Plot the data from each Watermark® sensor with a different color line so that the various depths can be easily distinguished. An Excel-based spreadsheet template for entering field data is available for free from the authors or from http://alfalfa.ucdavis.edu.

We prefer inverting the y-axis (the centibar readings) so that zero is at the top of the graph instead of the bottom (Figure 1). This simplifies interpretation. Using this orientation, the line on the graph drops as the soil dries and rises when the soil is wet. This pattern is more consistent with how one conceptually thinks of changes in soil moisture content.

The graph in Figure 1 is an example of effective irrigation management and illustrates how readings typically fluctuate from spring through the first alfalfa cutting. Soil moisture at the uppermost sensor normally declines first, as there is greater root activity in the upper portion of the soil profile than at deeper depths. There was also far more fluctuation in soil moisture at the shallow depths (1 and 2 feet), as noted by the oscillation in the lines, than at the deepest depth (4 feet). Again, this is because of more extensive root activity in this zone. Figure 1 illustrates effective irrigation management—irrigations occurred when the 1-foot sensor readings reached the appropriate range for this soil type (60–90 centibars). Figures 2 and 3 illustrate inadequate and excessive irrigation examples, respectively.

Recommended Values at Which to Irrigate Alfalfa and Pasture for Different Soil Types

Soil Type	Moisture Reading (centibars)
Sand or loamy sand	40–50*
Sandy loam	50–70
Loam	60–90
Clay loam or clay	90–120

*__Caution__: Soil moisture sensors may not be useful for very sandy soils with extremely low water holding capacity, as the sensors may not respond quickly enough to the rapid decline in soil moisture.

Note: These values were based on 50% depletion of available soil moisture for different soil types.

Interpreting Soil Moisture Data

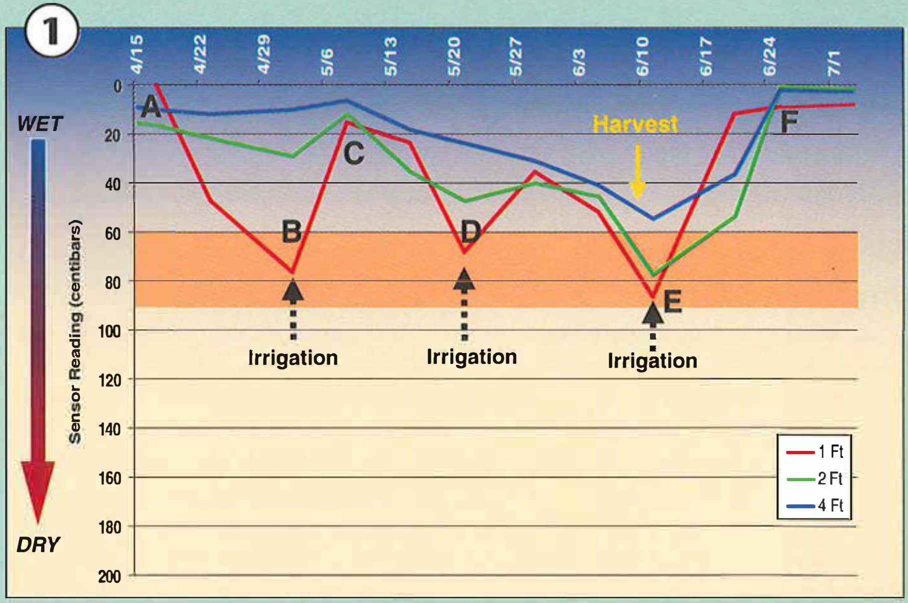


Figure 1. Proper Irrigation Management.

Shaded area indicates where irrigations should occur. At the start of the season the soil is moist from winter and spring rains—the readings are less than 20 centibars (**A**). Gradually the soil dries and the readings increase, beginning with the sensor located at the one-foot depth followed by the deeper depths. When the soil moisture reading dropped to near 80 in early May (**B**), irrigation water was applied and the centibar readings at all three depths went to below 20, indicating the soil profile had been refilled. The drying cycle resumed until a partial irrigation occurred in late May (**D**). A partial irrigation was needed to replenish enough soil moisture to carry the crop through the harvest period without excessive soil moisture depletion and crop stress. The first cutting occurred in early June [note point on graph when soil moisture content was lowest; (**E**)]. Following cutting, irrigation resumed until the soil moisture content at all three depths was restored (all readings below 20 centibars at point **F**).

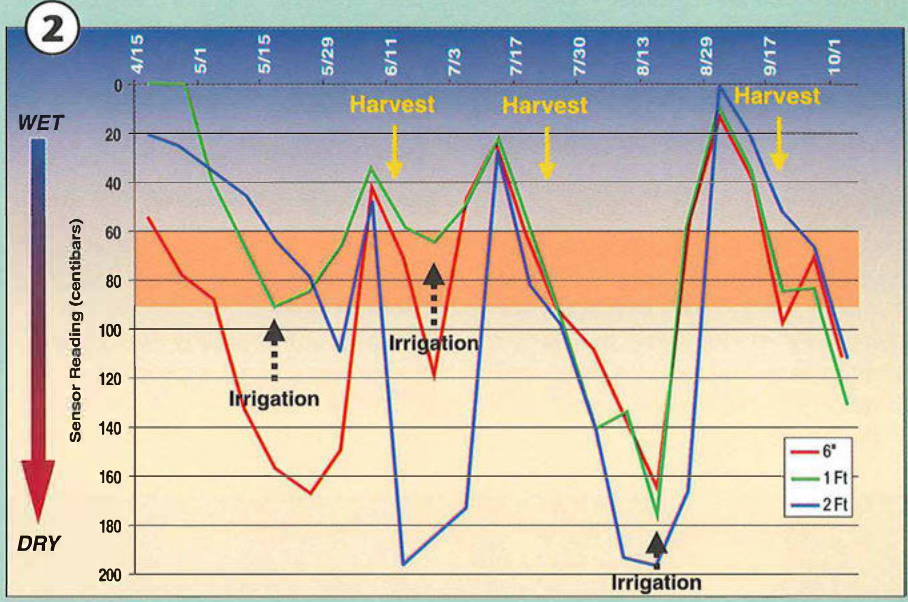


Figure 2. Under-irrigation example.

Soil moisture tension levels for an irrigated alfalfa/grass field. The first irrigation occurred too late, and soil moisture remained extremely low for much of the season. Not until late August was the soil profile refilled—too late for much benefit to the crop. This field would have benefitted from careful monitoring of soil moisture and timely early irrigation.

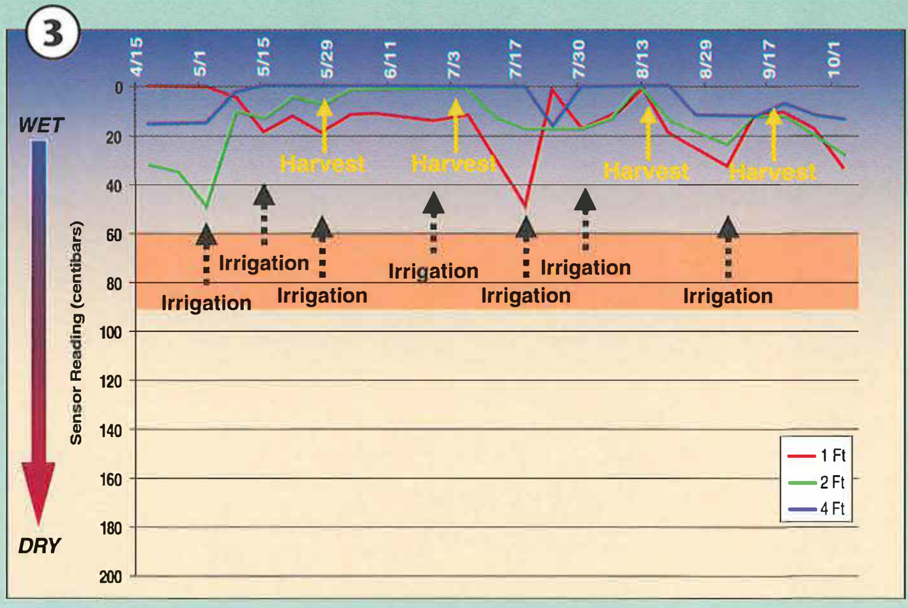


Figure 3. Over-irrigation example.

Soil moisture levels for an irrigated alfalfa field. Soil moisture tension never exceeded 50 centibars and remained below 30 centibars for most of the season. *(Irrigation should occur at 60–90 centibars; shaded area).* One or two irrigations could have been eliminated or less water applied per irrigation.

Using Soil Data to Guide Irrigation Decisions

Why Monitor Soil Moisture?

Soil moisture tension data can help 'train' the manager or irrigator to make wise irrigation decisions. Combined with observations of the crop and other irrigation scheduling techniques (e.g. the 'checkbook' method), soil moisture blocks can help you know what is happening in the soil, and to 'ground truth' your decisions. It can help answer questions such as:

When Do I Start Irrigating?

Figure 2 shows a real-life example of a field where irrigation was delayed too late in the spring. The first irrigation did not occur until early June, when the soil was way too dry (160 centibars at the 6-inch sensor). It is likely that moisture stress occurred and yield was reduced—monitoring would have triggered an earlier irrigation decision.

Is There Enough Deep Moisture?

It is important to have adequate soil moisture in the lower half of the root zone. Deep moisture serves as a reserve for use when needed, such as harvest periods during the hot summer. While the field in Figure 1 shows plenty of subsurface moisture, Figure 2 shows a field where moisture was excessively depleted at lower depths, stressing the plants. Information about a lack of deep moisture may enable a grower to take corrective action to refill the profile.

Am I Applying Enough Water?

Under-irrigation is a common hazard of forage production. Figure 2 shows a real-life example of a field that was watered too-infrequently throughout much of the growing season. Many of the readings are above 160 centibars, indicating very dry soil. All but the last irrigation was inadequate to wet the entire profile. Soil moisture monitoring indicates the grower should irrigate more frequently to correct this situation.

Am I Watering at the Wrong Time?

In some cases, water is applied at a time when it's not needed by the crop. In Figures 2 and 3, the growers irrigated late in the season (August) to fill the profile. However, irrigation was most likely unnecessary because the growing season was nearly over, and the crop needed less water. These irrigations probably could have been saved without reducing yield. Soil monitoring can help indicate when to stop watering, as well as when to start.

Am I Watering Too Much?

Figure 3 shows over-irrigation, or too-frequent irrigation. Soil moisture tension never exceeded 50 centibars, and for most of the season remained below 30 centibars, indicating a continually wet soil (the grower should have waited until soil moisture tension was 60-90 centibars). Maintaining the soil too wet resulted in higher than necessary pumping costs and an increased infestation of the summer annual weeds lambsquarters and pigweed. Based on this graph, one or two irrigations could have been omitted, or less water applied per irrigation, without reducing yield.

Match Irrigation to Crop Needs!

The principle behind irrigation management is to irrigate only enough to meet crop needs. Irrigation mistakes are easy to make, even for experienced growers. Soil moisture sensors improve the chances of making the right irrigation decisions.

Importance of Avoiding Over- or Under-Irrigation

Over-Irrigation

- Yield loss
- Diseases
- Nutrient losses through leaching
- Weed encroachment
- Power or water costs
- Environmental concerns

Under-Irrigation

- Yield loss
- Frost injury increased
- Weed encroachment

Installation and Management Recommendations

Site Selection

A critical part of installation is selecting an appropriate site for the sensors. Since irrigation of the whole field is based on the sensor readings, the sensors need to be in an area that represents the field. Locate the sensors in an area having the soil type typical of the field, uniform crop growth, and in an area that receives full uniform sprinkler or flood-irrigation coverage. If the sensors are placed in an area that is not representative, the results can be very misleading.

One sensor site per field is usually sufficient; however, if the field is variable, two sites are desirable. It may be helpful to install one of the sensors in a slightly sandier area of the field to use as an early indicator of when irrigation may be required.

Sensor Placement

Proper sensor placement is critical for accurately representing soil moisture in the crop root zone. We recommend installing two or three sensors at each evaluation site (Figure 5). One sensor should be in the upper one quarter of the root zone. Another should be toward the bottom of the root zone. When three sensors are used in an alfalfa field, install them at 1 ft., 2 ft., and 3.5 or 4 ft (depending on the depth of the soil). In cases where the rooting depth is more restricted, installations at 9 in., 1.5 ft., and 3 ft. are recommended. Because of shallower rooting in irrigated pastures, the sensors should be installed at 6 in., 1 ft., and 2 ft.

Three sensors present a more complete soil moisture picture and allow better evaluation of the depth reached with each irrigation.

The uppermost sensor indicates when to irrigate. The second sensor helps determine the depth of the last irrigation and is a check for the first sensor to make sure it is operating properly. The deepest sensor measures moisture reserves deep in the root zone. Maintain the deepest sensor within an acceptable range—not too dry (over 90 centibars) or not too wet (saturated conditions, readings less than 5 or 10 centibars).

Installation

Use a probe or coring device to create a hole slightly larger than the diameter of the sensor (See Figure 6). The sensor must be in direct contact with the surrounding soil. To ensure contact, prepare a small slurry (mixture of the surrounding soil and water) to pour into the hole before seating the sensors. As the sensor is pushed into the hole, the slurry at the bottom squeezes up around the sensor to provide good contact between the soil and sensor.

The wire leads come up from the sensors to the soil surface. Carefully back fill the hole so as not to damage the wires. A 4- to 6-inch length of 2-inch PVC with a screw-on cap works well and protects the wire leads from a swather or cattle. Dig a shallow (3- to 6-inch) trench for the wire leads coming from each sensor to the PVC housing. You can color code the wires to keep

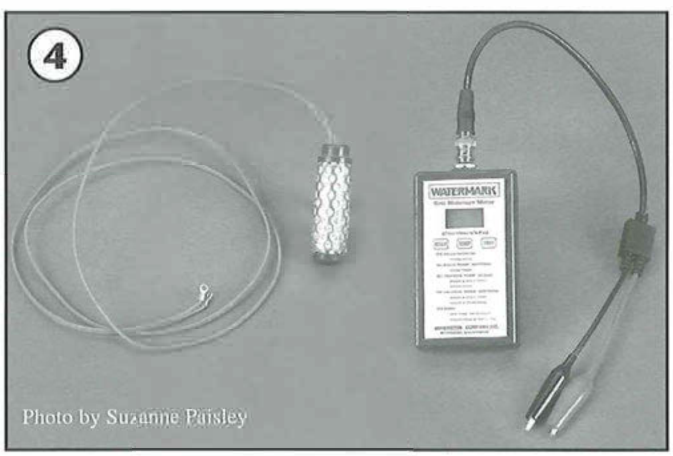


Figure 4. The Watermark® soil moisture sensor is an example of an electrical resistance block. Resistance blocks evaluate soil moisture by measuring the resistance between two electrodes imbedded in the sensor (A) using a calibrated portable meter (B). The blocks absorb moisture as the soil wets and release moisture as the soil dries—the higher the water content, the lower the electrical resistance.

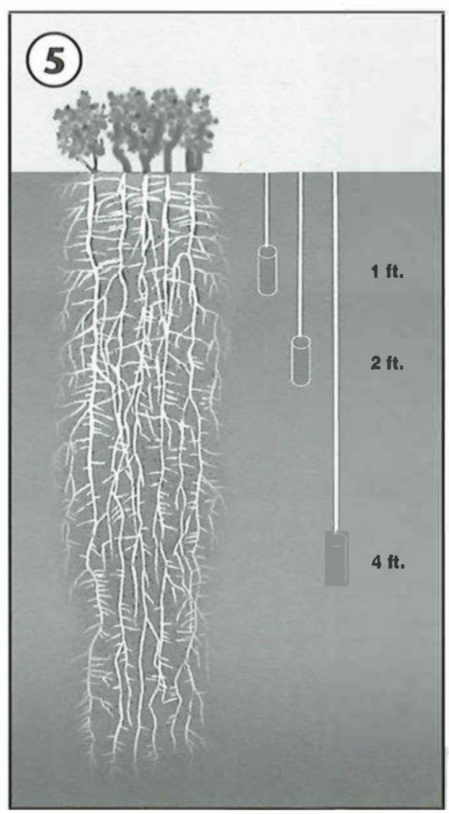


Figure 5. Two sensors at each evaluation site are acceptable but three are preferred because it provides a more complete picture of the soil moisture status at different depths, allowing the irrigator to determine the depth of the last irrigation. For alfalfa install sensors at 1 ft., 2 ft., and 4 ft. (9 inches, 1.5 ft. and 3 ft. in shallow soils). For pasture install sensors at 6 in., 1 ft. and 2 ft.

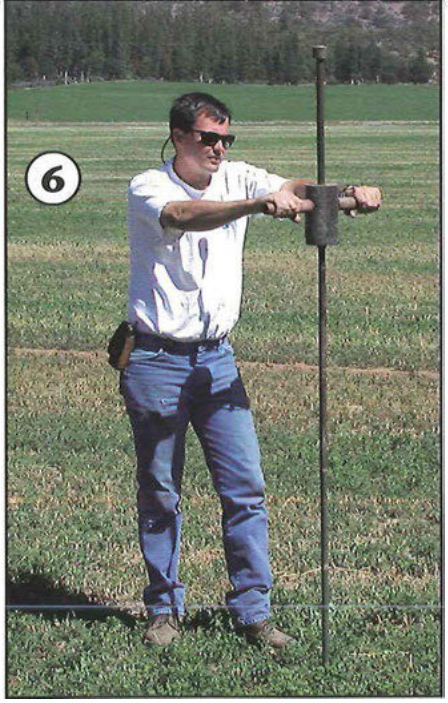


Figure 6. This steel rod is pounded into the soil to create a hole slightly larger than the diameter of the sensor. A coring device can also be used. Direct contact between the sensor and the soil is essential for reliable soil moisture readings.

track of the depth of the sensors by tying a small piece of colored wire to each lead.

An alternative installation involves gluing a section of PVC pipe onto each sensor and feeding the wires through the pipe (Figure 7). This installation allows the sensors to be retrieved and reused. One-half inch Class 315 PVC has an inside diameter that fits exactly over the top of the sensor collar. Use PVC to ABS cement to weld the sensor to the PVC. A cap can be fitted directly on the pipe to house the wire leads and the depth of the sensor engraved on the cap.

How Often to Take Soil Moisture Readings

How often you take soil moisture readings depends on their intended use. Weekly readings should provide an overall picture of the seasonal soil-moisture status of the field for evaluating current irrigation practices. However, if the Watermark® readings are used for irrigation scheduling, readings should be taken at least twice a week, especially immediately before and after an irrigation. Commercial data logging devices are available that constantly record readings at predetermined intervals.

Conclusion

Irrigation management for alfalfa and irrigated pastures can be difficult—growers must schedule around harvests, making it problematic to use many irrigation-scheduling techniques. However, years of research and field experience have shown that soil moisture sensors are very useful to diagnose changes needed and to fine-tune irrigation practices. Relatively minor adjustments in irrigation practices could pay large dividends in increased yield or water savings.

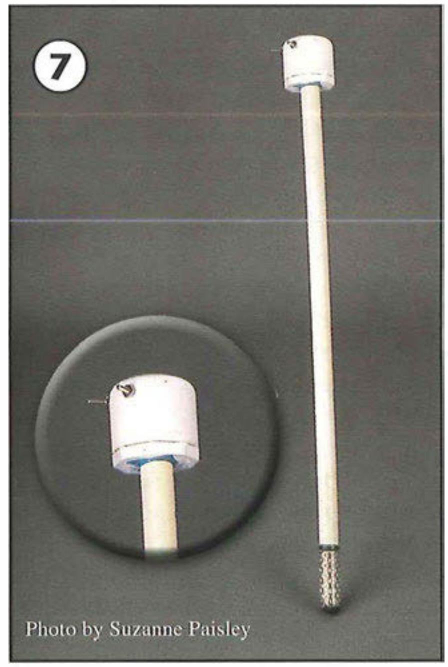
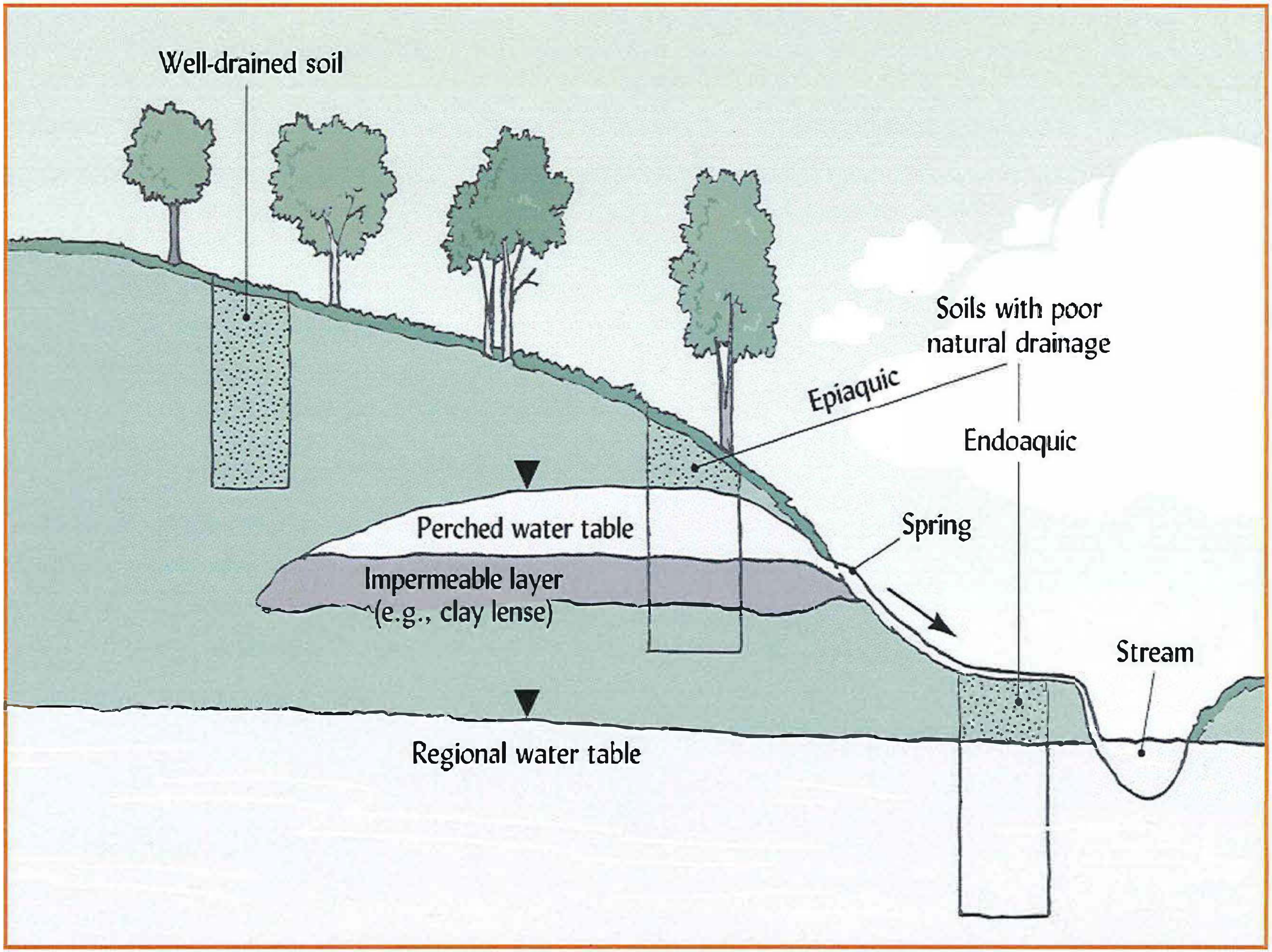


Figure 7. Soil moisture sensors can be glued to the end of PVC pipe. Wire leads from the sensor are connected to bolts protruding from a PVC cap for easy access while taking readings. This installation allows the sensors to be retrieved and reused.

Soil Drainage

- Soil drainage classes
  - Refer to the extent of seasonal wetness in soil not the rate of water movement
  - Largely a function of water table depth
    - *Well drained soils* have a deeper water table
    - *Somewhat poorly drained soils* have a fluctuating water table
      - Mottles or redoximorphic features present
    - *Poorly drained soils* have a shallow water table for long periods
      - Usually require management modification to be useful


Well-drained soil
Soils with poor natural drainage
Epiaquic
Endoaquic
Perched water table
Spring
Impermeable layer (e.g., clay lense)
Stream
Regional water table

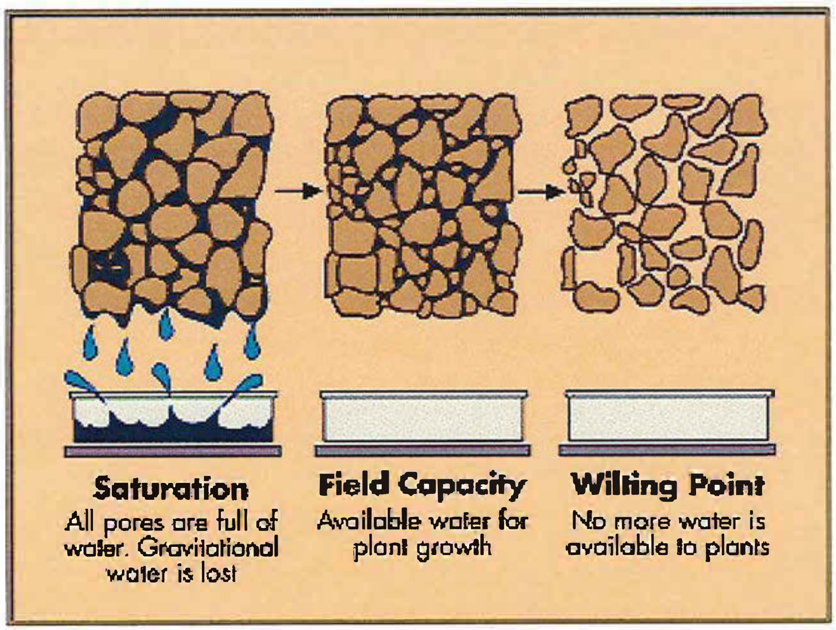
Water Absorption by Plants

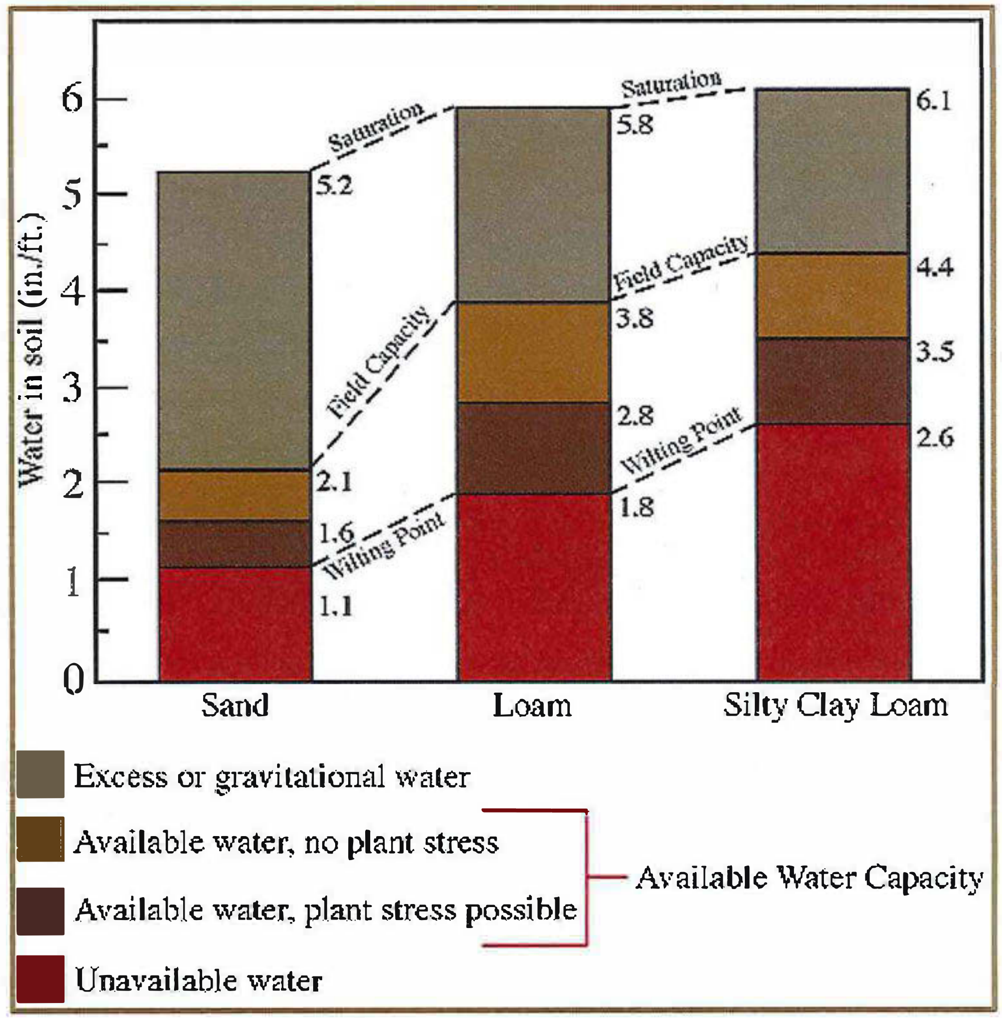
- Usually only a small amount of water is adjacent to plant roots at a given time
- Roots supplied with water by:
  - Capillary movement of water to root
    - Influenced by potential difference between root and rhizosphere
      - Soil moisture content, osmotic potential, plant species
  - Growth of roots into moist soils

RECAP: Water Content Terms

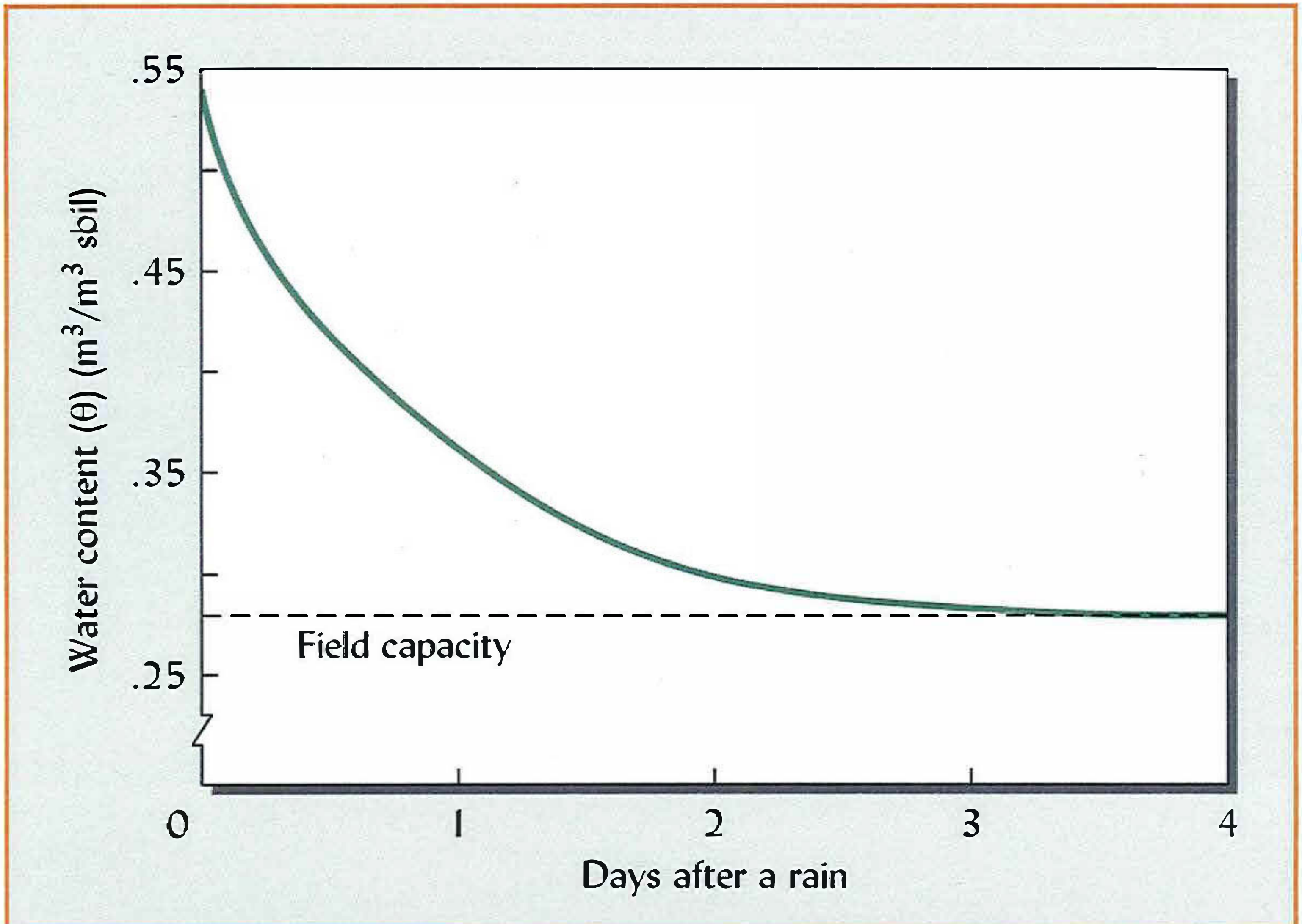
- Saturated:
  - all pores are filled with water
- Field capacity:
  - macropores are drained of water (by gravity)
  - maximum amount of water available to plants
- Permanent wilting point:
  - Point at which plant roots can no longer extract water

Water Content Terms





Water content of a soil over time after a rain



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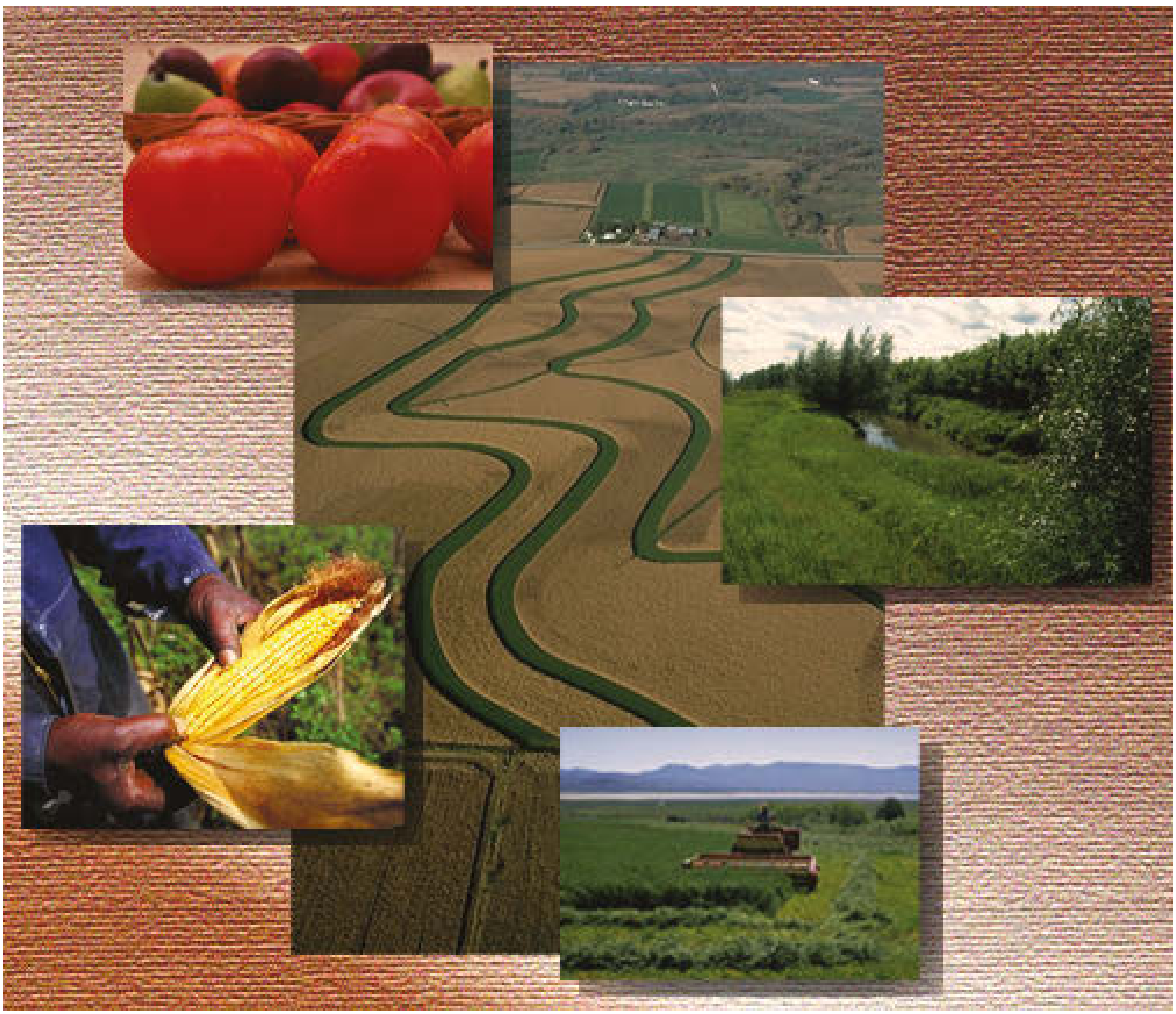


National Agronomy Manual

Issued February 2011

Subpart 504A Managing soil moisture on nonirrigated lands

504.00 Soil moisture management overview

Soil moisture management in dryland agriculture is the most critical factor in producing sustainable crop and forage production systems. Without water, no living thing would survive. In relation to crop and forage production, the knowledge of soil water and its proper management has dramatic effects on yields, crop/forage quality, nutrient uptake, and soil health. Climatic factors, crop selection, rotational influences, tillage systems, topography, as well as inherent soil characteristics, all interrelate in assessing the availability of adequate water necessary for successful crop and forage production.

(a) Soil water holding capacity

The potential for a soil to hold water is an important factor in designing a crop production system. Total water held by a soil is called water-holding capacity. However, not all soil water is available for extraction by plant roots. The volume of water available to plants that a soil can store is referred to as available water capacity (AWC).

(b) Available water capacity

Available water capacity is the traditional term used to express the amount of water held in the soil available for use by most plants. It is dependent on crop rooting depth and several soil characteristics. Units of measure are expressed in various terms:

- Volume unit as inches of water per inch or per foot of soil depth
- Gravimetric percent by weight
- Percent on a volume basis

In fine textured soils and soils affected by salinity, sodicity, or other chemicals, a considerable volume of soil water may not be available for plant use.

Water occurs in three forms besides occurring in the form of vapor. *Capillary* water, held in the soil by surface tension, is the water used mostly by plants. When plants begin to wilt, the soil may still contain 2 to 17 percent moisture, depending upon its texture and humus content. Amounts of water below this “permanent wilting point” are largely unavailable to plants. *Gravitational* water is water that moves downward by gravitational forces and may percolate beyond reach of the roots of some plants. *Hydroscopic* water, which is moisture retained by an air-dry soil, is adsorbed on soil particles with such force that it is not available to plants.

Soil-water potential, more correctly, defines water available to plants. It is defined as the amount of work required per unit quantity of water to transport water in soil. The concept of soil-water potential replaces terms such as gravitational, capillary, and hygroscopic water. In the soil, water moves continuously in the direction of decreasing potential energy or from higher water content to lower water content. As a plant takes up water from the soil, the concentration of water in the soil immediately adjacent to its roots is reduced. Water from the surrounding soil then moves into the soil directly around the roots.

For practical reasons, the terms and concepts of field capacity and permanent wilting point are normally used to define the higher and lower limits of available amounts of water. Units of megapascals [MPa (metric units)] or bars or atmospheres (English units) are generally used to express soil water potential. One MPa is equal to 10 bars or atmospheres.

Field capacity of soils, i.e. the amount of water held against the force of gravity, typically ranges from 1 to 2 inches in each foot of soil. The finer the particles (silts and clays) the more water the soil holds. Extremely coarse sandy soils are typically unable to store moisture in sufficient quantities for crop growth under dry land systems.

The field capacity of a well-drained soil is the amount of water held by that soil after free water has drained due to gravity. For coarse textured soil, drainage occurs soon after a rain event because of relatively large pores and low soil particle surface tension. In fine textured soil, drainage takes much longer because of smaller pores and their horizontal shape. Major soil properties that affect field capacity are texture, organic matter content, structure, bulk density, and strata within the profile that restrict water movement. Generally, fine textured soil holds more water than coarse textured soil. Some soils, such as some volcanic and organic soils, are unique in that they can retain significant volumes of water at tensions less than one-tenth bar, thereby giving them a larger available water capacity.

An approximation of field capacity soil-water content level can be made best in the laboratory. It is the water retained in a soil when subjected to a tension of –0.01 MPa [–0.1 atmosphere (bar)] for sandy soils and –0.03 MPa for other finer textured soils.

Absorption—Plants absorb water and also the substances dissolved in it including nitrogen and other mineral elements, largely through root hairs. The root hairs absorb water by osmosis. The more a plant needs water the more vigorously it is absorbed, provided the water supply remains ample. It is also possible for water to be extracted from the roots, as can happen in the case of highly saline soils and saline soil solution.

Nutrients, although taken up by the plant through root hairs (predominantly) are absorbed independently of the rate of water intake, being taken into the plant as ions by diffusion.

Permanent wilting point is the soil-water content at which most plants cannot obtain sufficient water to prevent permanent tissue damage. The lower limit to the available water capacity has been reached for a given plant when it has so exhausted the soil moisture around its roots as to have irrecoverable tissue damage, thus yield and biomass are severely and permanently affected. The water content in the soil is then said to be the permanent wilting percentage for the plant concerned.

Experimental evidence shows that this water content point does not correspond to a unique tension of 1.5 MPa for all plants and soils. The quantity of water a plant can extract at tensions greater than this figure appears to vary considerably with plant species, root distribution, and soil characteristics. Some plants show temporary plant moisture stress during hot daytime periods and yet have adequate soil moisture. In the laboratory, permanent wilting point is determined at 1.5 MPa tension. Unless plant specific data are known, any water remaining in a soil at greater than 1.5 MPa tension is considered unavailable for plant use.

Soil characteristics affecting the available water capacity are texture, structure, bulk density, salinity, sodicity, mineralogy, soil chemistry, and organic matter content. Of these, texture is the predominant factor in mineral soil. Because of the particle configuration in certain volcanic ash soil, the soil can contain very high water content at field capacity levels. This provides a high available water capacity value. Table 508A–1 displays average available water capacity based on soil texture.

Soil pore space

Soil is composed of soil particles, organic matter, water, and air. The pore space (called porosity) found in soil between mineral particles and organic matter is filled with either air or water. The pore space both contains and controls most of the functions of soil. It is not just the total amount of pore space that is importance but also the size and distribution of pores, and the continuity between them that determines function and behavior of soil.

Pore space allows movement of water and air along with the growth of roots. Dense soil (heavy clay) has a low AWC because of decreased pore space. Density can make AWC differences of less than 50 percent to greater than 30 percent compared to average densities. Light (sandy) soils generally have bulk densities greater than soils with high clay content. Sandy soils have less total pore space than silt and clay soils. Gravitational water flows through sandy soils much faster because the pores are much larger. Clayey soils usually contain more water than sandy soils because clay soils have a larger volume of small, flat-shaped pore spaces that hold capillary water. Clay soil particles are flattened or plate-like in shape, thus, soil-water tension is also higher for a given volume of water. When the percent clay in a soil increases over about 40 percent, AWC is *reduced* even though total soil-water content may be greater. Permeability and the ability of a soil to drain are directly related to the volume, size, and shape of pore space.

Uniform plant root development and water movement in soil occurs when the soil profile bulk density is uniform; a condition that seldom exists in the field. Generally, soil compaction occurs in all soils where tillage implements and wheel traffic are used. Soil compaction increases bulk density but decreases pore space, decreasing root development, oxygen content, water movement, and availability.

Compaction—A good soil for crop production contains about 25 percent water and 25 percent air by volume. This 50 percent is referred to as pore space. The remaining 50 percent consists of soil particles. Anything, for example tillage and wheel traffic that reduces pore space, results in a dense soil with poor internal drainage and reduced aeration.

Soil compaction can be a serious production problem. Over the years, field implements have become bigger and heavier, and some cultivation is performed when soil is too moist. Because compacted soil has smaller pores and fewer natural channels, water infiltration can be drastically reduced. This causes greater surface wetness, more runoff, which in turn increases erosion, and longer soil drying time. Wet fields delay planting and harvesting. Plant roots do not grow well in dense or compacted soil resulting in inadequate moisture and nutrients reaching the plant.

Figure 504–1 shows how soil moisture affects compaction depth. A given load and tire size causes greater deep compaction on wet soil than dry. Sod-forming crops such as alfalfa and clover, which in the past were typically included in crop rotations, provide greater support at the soil surface than bare soil.

Table 504–1 Available water capacity (AWC) by soil texture

Texture symbol	Texture	AWC range (in/in)	AWC range (in/ft)	Estimated typical AWC (in/ft)
COS	Coarse sand	0.01–0.03	0.1–0.4	0.25
S	Sand	0.01–0.03	0.1–0.4	0.25
FS	Fine sand	0.05–0.07	0.6–0.8	0.75
VFS	Very fine sand	0.05–0.07	0.6–0.8	0.75
LCOS	Loamy coarse sand	0.06–0.08	0.7–1.0	0.85
LS	Loamy sand	0.06–0.08	0.7–1.0	0.85
LFS	Loamy fine sand	0.09- 0.11	1.1–1.3	1.25
LVFS	Loamy very fine sand	0.10–0.12	1.0–1.4	1.25
COSL	Coarse sandy loam	0.10–0.12	1.2–1.4	1.3
SL	Sandy loam	0.11–0.13	1.3–1.6	1.45
FSL	Fine sandy loam	0.13–0.15	1.6–1.8	1.7
VFSL	Very fine sandy loam	0.15–0.17	1.8–2.0	1.9
L	Loam	0.16–0.18	1.9–2.2	2.0
SIL	Silt loam	0.19–0.22	2.3–2.6	2.45
SI	Silt	0.16–0.18	1.9–2.2	2.0
SCL	Sandy clay loam	0.14–0.16	1.7–1.9	1.8
CL	Clay loam	0.15–0.17	1.8–2.0	1.9
SICL	Silty clay loam	0.17–0.19	2.0–2.3	2.15
SC	Sandy clay	0.15–0.17	1.8–2.0	1.9
SIC	Silty clay	0.15–0.17	1.8–2.0	1.9
C	Clay	0.14–0.16	1.7–1.9	1.8

504.01 Climatic and precipitation

Crops are generally grown most successfully when grown in regions where they are well adapted. Crop production shows patterns of geographic segregation despite the fact that many crops may grow well over wide areas. One of the principal factors that influence localization is climate.

Climate is a major factor for determining the suitability of a crop for any given area. Climatic differences are due chiefly to the variations in latitude, altitude, distances from large water bodies, ocean currents, and direction and intensity of winds.

There are three distinct (major) climatic regions recognized in the US. The first is the narrow strip of territory from the Pacific Coast to the Cascade and Sierra Nevada mountains, an oceanic climate where rainfall ranges from less than 10 inches (Southern California) to over 100 inches per year in the Northwest. Winters are mild in this region, while summers in the northern portion and along the coastline are cooler. The second region is the upland plateau from these mountains eastward to approximately the 100th meridian (fig. 504–2). The climate in this region is characterized by great extremes of temperature between day and night and between winter and summer. It is also characterized by irregular approach of seasons, deficient rainfall, lower humidity, and relatively unobstructed winds. The limited rainfall that occurs can be sporadic and often torrential. The third region is from the 100th meridian east to the Atlantic, where conditions are again modified by the Great Lakes and ocean.

Frost—In many areas, potential frost is a major concern for crop and forage production. Frost not only affects growing tissues, it also has an effect on soil. Frost action can cause upward or lateral movement of soil by formation of ice lenses. Frost can break compact and clayey layers into more granular forms at shallow depths. It can also break large clay aggregates into smaller aggregates that are more easily transported by wind. Frost heaving can have detrimental effects on conservation structures and even destroy taprooted perennial crops.

Precipitation—In dryland systems, rainfall (amount and timing) is the most limiting factor affecting crop production systems. In semi arid regions, such as the Great Plains and Great Basin, managing the scanty precipitation is so vitally important that it takes precedence over all other manageable factors.

Figure 504–1 Effects of compaction

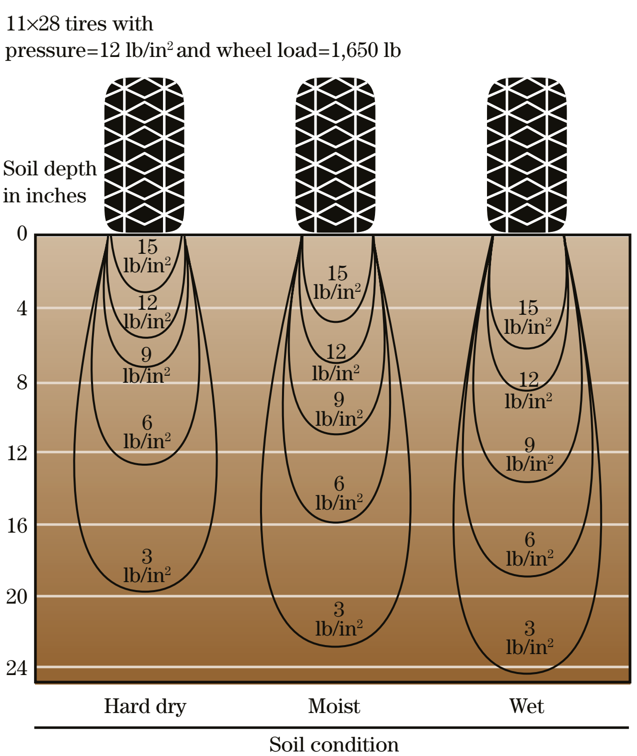
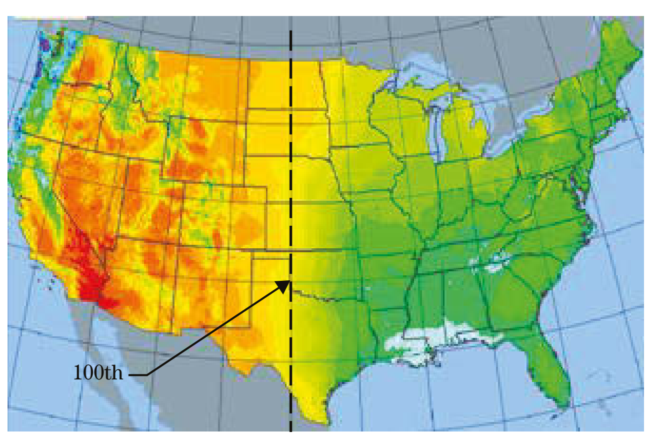


Figure 504–2 Climatic regions of the United States



Crop regions are often classified based on average annual precipitation. The *arid region* is where the average annual precipitation is 10 inches or less. Irrigation is necessary for successful crop production in most of these areas. The *semi arid* region is considered to be that where precipitation varies from 10 to 20 inches. Conservation tillage along with crop varieties and rotations adapted to dry farming regions, and sometimes irrigation, are necessary for successful production. The annual precipitation in *semi-humid* areas ranges from 20 to 30 inches. This amount of precipitation may not be adequate for satisfactory crop yields unless moisture management methods that best utilize growing season soil moisture are followed. For example, in the southern Great Plains, seasonal evapotranspiration is high requiring conservation practices that reduce soil evaporation. The humid region is regarded as the area where annual precipitation is more than 30 inches. Conservation of moisture in this region is not necessarily the dominant factor in crop production systems.

Effective rainfall—The effectiveness of a given amount of rainfall within a crop production system depends upon the time of the year it falls and the intensity of individual rainfall events. Seasonal evaporation may be equally critical.

Total rainfall can fluctuate widely from year to year along with its timeliness. Rainfall has its greatest value when it falls during the growing season, which is typically between April 1 and September 30 in most regions. The critical period for moisture to be available, for most crops, occurs just before or immediately after flowering. For instance, in the Golden Triangle in Montana, where growing season precipitation average about 5 inches of rainfall, a total of less than 1 inch of precipitation had fallen since January. A spring wheat crop was planted in hopes of rains. Due to lack of rainfall, the spring wheat was only 12 inches tall (half of the normal height) when it started into the boot stage. The rain finally came and in one week of continuous, slow rainfall, 4 to 5 inches soaked into the ground. Record yields were harvested with only half of the green vegetation. Conversely, in a year with greater than average soil moisture, the spring wheat planting grew tall and lush only to run out of soil moisture. With no growing season rainfall, seed heads formed on the tall stalks. It was too late when 4 inches of rain poured out of the sky in one day, much of it running off the fields. This type of rainfall is not effective. In dry land farming, timing of precipitation is vitally important.

Soil water—Water is the most important constituent in the soil in relation to crop and forage production. Additionally, physical soil characteristics have a major impact on water infiltration, movement, storage, and availability of water within the soil profile. Some of these characteristics include soil texture, bulk density, structure, pore space, organic matter content, salinity and sodicity as well as other inherent soil characteristics.

Water can move in soils under gravity (i.e. drainage) and under a suction gradient (capillary). The rate of movement is controlled by the size and continuity of the pores containing the water, by the pressure or suction gradient, and by the viscosity of the water. Water can only move through existing water-filled passages. It cannot move across or down an air space except under exact extreme conditions.

Water infiltration—Water infiltration is the process of water entering the soils from the soil surface. The rate at which water enters the soil, considered either infiltration rate or permeability of the soil, depends on the portion of coarser pores on or near the soil surface. The rate itself is controlled by every factor which affects the number and stability of larger pores. Infiltration rates are directly affected by factors that are somewhat controlled by management including tillage practices, amounts of surface residue, soil organic matter, salinity, and sodicity. Infiltration rates are also heavily reduced if the pores at the surface become filled with mud, as may happen if muddy water flows over the land or during heavy rain storms if the surface is not protected from mechanical shattering of the last-falling heavy rain drops.

Infiltration rates change during a rainfall event and typically become slower over time. They may also decrease over the growing season because of cultivation and harvest equipment. This is especially true if operations are completed during higher soil-water levels. Macropores, such as cracks of worm holes affect internal drainage and thus may play significant roles in infiltration rates.

504.02 Crop water requirements

Water is required for all plant growth and is needed in much larger quantities than any essential nutrient. The difference between water and nutrients is that usually a large proportion of nutrients absorbed by the plant are retained, whereas, water is continuously taken up by the plant and then evaporated inside the stomata and diffused into the air.

The rate of water transfer from the soil into the air by the plant is controlled by four separate processes:

- Transfer of water from the soil into the vascular system,
- Transfer from the vascular system through the protoplasm to the leaf cells bounding the stomata,
- Water evaporates in stomata and from leaf surface,
- Transfer of water vapor from inside stomata in the air by diffusion or convection.

Plants *normally* transfer water from the soil to the leaf cells faster than it is dissipated from the leaves as vapor. But, under conditions of high evaporation or limited water supply in the soil, the root cells may not be able to transfer water from the soil to the vascular system as fast as leaf cells are dissipating it. In this situation, the leaves will begin to lose water, causing most species of plants to lose turgor and begin to wilt.

Shortage of water in the leaf has several effects besides causing it to wilt. The stomata close, cutting down on transpiration losses and reducing photosynthesis. Leaf cells loose water causing cell sap to rise, causing death of the cells and eventually the entire leaf (and if continued the entire plant).

Farm crops typically react to prolonged drought by shedding their leaves, thus reducing the amount of water they transpire and hence their demands on the soil water. However, crops differ considerably in the severity of drought they can withstand before all the leaves have been lost or died. Most young plants are very dependent on an adequate supply of water and are unable to withstand any appreciable drought. But, as plants grow older, they can usually survive periods of water shortage without any serious injury. Some crops are capable of going dormant during periods of drought, which is a characteristic of leaf construction. The direct effect of drought on a crop is based on the amount of leaf the crop is able to carry.

Crop evapotranspiration (ETc), sometimes called crop consumptive use, is the amount of water that plants use in transpiration and building cell tissue plus water evaporated from an adjacent soil surface. Seasonal local crop water use requirements are essential for planning crop production systems.

Evaporation—Evaporation is the process whereby liquid water is converted to water vapor (vaporization) and removed from the evaporating surface. Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils and wet vegetation. Energy is required to change the state of the molecules of water from liquid to vapor. Direct solar radiation and, to a lesser extent, the ambient temperature of the air provide this energy. As evaporation proceeds, the surrounding air becomes gradually saturated and the process will slow down and might stop if the wet air is not transferred to the atmosphere. The replacement of the saturated air with drier air depends greatly on wind speed. Hence, solar radiation, air temperature, air humidity, and wind speed are climatological parameters to consider when assessing the evaporation process.

Where the evaporating surface is the soil surface, the degree of shading of the crop canopy and the amount of water available at the evaporating surface are other factors that affect the evaporation process. Frequent rains, irrigation, and water transported upwards in a soil from a shallow water table wet the soil surface. Where the soil is able to supply water fast enough to satisfy the evaporation demand, the evaporation from the soil is determined only by the meteorological conditions. However, where the interval between rains (or irrigation) becomes large and the ability of the soil to conduct moisture to the surface is small, the water content in the topsoil drops and the soil surface dries out.

Transpiration—Transpiration consists of the vaporization of liquid water contained in plant tissues and the vapor removal to the atmosphere. Crops predominately lose their water through stomata. These are small openings on the plant leaf through which gases and water vapor pass. The water, together with some nutrients, is taken up by the roots and transported through the plant. The vaporization occurs within the leaf, namely in the intercellular spaces, and the vapor exchange with the atmosphere is controlled by the stomatal aperture. Nearly all water taken up is lost by transpiration and only a tiny fraction is used within the plant.

Transpiration, like direct evaporation, depends on the energy supply, vapor pressure gradient, and wind. Hence, radiation, air temperature, air humidity, and wind terms should be considered when assessing transpiration. The soil water content and the ability of the soil to conduct water to the roots also determine the transpiration rate, as do waterlogging and soil water salinity. The transpiration rate is also influenced by crop characteristics, environmental aspects, and cultivation practices. Different kinds of plants may have different transpiration rates. Not only the type of crop, but also the crop development, environment and management should be considered when assessing transpiration.

504.03 Irrigation water and plant growth

Irrigation water is applied to soil to supply adequate water quantities to grow crops and forages that may not otherwise be possible with dryland cropping systems. Irrigation water is applied to replenish water removed from the soil by evaporation, by growing plants (transpiration) and to some extent by drainage below the root zone. In some cases it is used to flush minerals from the root zone (salts) annually.

Water application is completed in a number of different ways. Methods of application depend upon the species of crop or forages being grown, soil characteristics, topography of the land, the cost of the water, and the cost of various delivery systems. The amount of water used and how often it is applied are determined by crop needs, the need for deep leaching (flushing out salts), local climatic conditions, and other interrelated factors. Successful irrigation required careful management of both crops and water.

All water used for irrigation contains some dissolved salts. Suitability of water for irrigation strongly depends on the kinds and amounts of salts present. Needless to say, salts in irrigation water have a direct impact on the plant and soil, and therefore on the properties of soils and the production of plants.

Irrigators should know the effects that their irrigation water and irrigation practices might have on their crops and forages including:

- the salt content of the soil (salinity)
- the sodium status of the soil
- rate of water penetration into the soil
- presence of elements which may be toxic to crops/forages

Water is held largely as film around each soil particle (see National Agronomy Manual Subpart 508A for Agronomic Soil Basics). The thinner these films are, the tighter they are held, and the greater the suction needed to remove the water. Right after an irrigation event, the films of water are thick and *not* held tightly by the soil. After some days, with free drainage, about half of this weakly held water moves deeper into the soil profile and, if additional water is not applied, free drainage ceases. This is the point called *field capacity*. Anytime water is below field capacity, gravity is not longer a significant source of water movement in the profile. Most of the water removed, at this point, is done so by growing plant roots. Plants have the capability of removing about one-half of the water held at field capacity. After that point, the soil holds on to water so tightly that plants cannot extract it, and leads to wilting if additional water is not applied.

(a) When to irrigate

Information pertaining to soil and crop characteristics is also important for irrigated cropping systems. It is vital for proper irrigation water management to accurately determine plant available soil water. Detailed information including soil texture, structure, layering, water-holding capacity, and soil depth, rooting pattern and depths, and crop susceptibility to stress are typically used to determine when to irrigate and how much water to apply.

(b) Tools and techniques

There are several tools and techniques that can be utilized to monitor or measure soil water for purposes of scheduling irrigation including:

- Soil feel and appearance method
- Gravemetric sampling
- Tensiometers
- Porous blocks
- Neutron probe

Scheduling routine sampling is important in any of the methods. Soil and water should be measured or monitored at a minimum of two depths in the expected crop root zone in several locations within a field.

504.04 Methods for determining crop evapotranspiration

Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. Apart from the water availability in the topsoil, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. This fraction decreases over the growing period as the crop develops and the crop canopy shades more and more of the ground area. When the crop is small, water is predominately lost by soil evaporation, but once the crop is well developed and the canopy completely covers the soil, transpiration becomes the main process. At planting nearly 100 percent of evapotranspiration (ET) comes from evaporation, while at full crop cover more than 90 percent of ET comes from transpiration.

(a) Weather parameters

The principal weather parameters affecting ET are radiation, air temperature, humidity, and wind speed.

(b) Crop factors

The crop type, variety, and development stage should be considered when assessing the ET from crops. Differences in resistance to transpiration, i.e. crop height, crop roughness, reflection, ground cover and crop rooting characteristics result in different ET levels in different types of crops under identical environmental conditions.

(c) Management and environmental conditions

Factors such as soil salinity, poor land fertility, limited application of fertilizers, the presence of hard or impenetrable soil horizons, the absence of control of diseases and pests and poor soil management may limit the crop development and reduce the evapotranspiration. Other factors to be considered when assessing ET are ground cover, plant density, and the soil water content. The effect of soil water content on ET is conditioned primarily by the magnitude of the water deficit and the type of soil. On the other hand, too much water will result in waterlogging which might damage the root and limit root water uptake by inhibiting respiration.

When assessing the ET rate, additional consideration should be given to the range of management practices that act on the climatic and crop factors affecting the ET process. Cultivation practices and the type of irrigation method can alter the microclimate, affect the crop characteristics, or affect the wetting of the soil and crop surface. A windbreak reduces wind velocities and decreases the ET rate of the field directly beyond the barrier. The effect can be significant especially in windy, warm, and dry conditions although evapotranspiration from the trees themselves may offset any reduction in the field. Soil evaporation in a young orchard, where trees are widely spaced, can be reduced by using a well-designed drip or trickle irrigation system. The drippers apply water directly to the soil near trees, thereby leaving the major part of the soil surface dry, and limiting the evaporation losses. The use of mulches, especially when the crop is small, is another way of substantially reducing soil evaporation.

(d) Direct measurement of crop evapotranspiration

Evapotranspiration is not easy to measure. Specific devices and accurate measurements of various physical parameters or the soil water balance in lysimeters are required to determine ET. The methods are often expensive, demanding in terms of accuracy of measurement and can only be fully exploited by well-trained research personnel.

Several methods that one can employee to directly measure evapotranspiration including

- lysimetry
- soil-water balance (inflow-outflow)
- energy balance and microclimate method
- others

These methods require localized and detailed measurements of plant water use. Detailed soil moisture monitoring in controlled self contained devices (lysimeters) is probably the most commonly used.

(e) Estimated crop evapotranspiration

There are numerous methods for estimating evapotranspiration based on local crop and climatic factors. The simplest methods are equations that generally use only mean air temperature. The more complex methods are described as energy equations. They require real time measurements of solar radiation, ambient air temperature, wind speed/movement, and relative humidity/vapor pressure. Most of these equations adjust for the reference crop ET with lysimeter data.

Selection of the method used for determining local crop ET depends on location, type, reliability, timeliness, and duration of climatic data; natural pattern of evapotranspiration during the year; and intended use intensity of crop evapotranspiration estimates.

Although any crop can be used as the reference crop, clipped grass is the reference crop of choice. Some earlier reference crop research, mainly in the West, used 2-year-old alfalfa (ETr). With a grass reference crop (ETo) known, ET estimates for any crop at any stage of growth can be calculated by multiplying ETo by the appropriate crop growth stage coefficient (kc), usually displayed as a curve or table. The resulting value is called crop evapotranspiration (ETc).

The following methods and equations used to estimate reference ET_c. ETo methods and equations are described in detail in the National Engineering Field Handbook, Part 623, Chapter 2, Irrigation Water Requirements (1990). The reference crop used is clipped grass. Crop coefficients are based on local or regional growth characteristics. The Natural Resources Conservation Service (NRCS) recommends the following methods:

- Temperature method
  - FAO Modified Blaney-Criddle
  - Modified Blaney-Criddle
- Energy method
  - Penman-Monteith method
- Radiation method
  - FAO Radiation method

Evaporation pan method—The FAO Modified Blaney-Criddle, Penman-Monteith, and FAO Radiation equations represent the most accurate equations for these specific methods. They are most accurately transferable over a wide range of climate conditions.

The intended use, reliability, and availability of local climatic data may be the deciding factor as to which equation or method is used. For estimation of monthly and seasonal crop water needs, a temperature-based method generally proves to be quite satisfactory.

The FAO Modified Blaney-Criddle equation uses long-term mean temperature data with input of estimates of relative humidity, wind movement, and sunlight duration. This method also includes an adjustment for elevation. The FAO Radiation method uses locally measured solar radiation and air temperature.

Crop ET and related tables and maps can be included to replace or simplify crop ET calculations. These maps and tables would be locally developed, as needed.

(f) Critical growth periods

Plants must have ample moisture throughout the growing season for optimum production and the most efficient use of water. This is most important during critical periods of growth and development. Most crops are sensitive to water stress during one or more critical growth periods in their growing season. Moisture stress during a critical period can cause an irreversible loss of yield or product quality. Critical periods must be considered with caution because they depend on plant species as well as variety. Some crops can be moderately stressed during noncritical periods with no adverse effect on yields. Other plants require mild stress to set and develop fruit for optimum harvest time (weather or market). Critical water periods for most crops are displayed in table 504-2.

(g) Rooting depth

The soil is a storehouse for plant nutrients, an environment for biological activity, an anchorage for plants, and a reservoir for water to sustain plant growth. The amount of water a soil can hold available for plant use is determined by its physical and chemical properties. Figure 504–3 provides a typical diagram of how soil water is extracted.

Crops extract water in varying amounts depending on depth into the rooting zone. Crop rooting density with depth is generally not uniform. Additionally, the rate

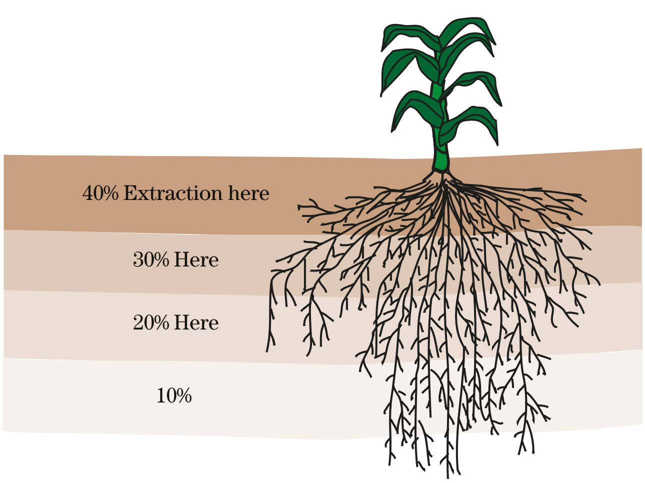
Table 504–2 Critical periods for plant moisture stress

Crop	Critical period	Comments
Alfalfa	At seedling stage for new seedlings, just after cutting for hay, and at start of flowering stage for seed production	Any moisture stress during growth period reduces yield Soil moisture is generally reduced immediately before and during cutting, drying, and hay collecting
Beans, dry	Flowering through pod formation	
Broccoli	During head formation and enlargement	
Cabbage	During head formation and enlargement	
Cauliflower	During entire growing season	
Cane berries	Blossom through harvest	
Citrus	During entire growing season	Blossom and next season fruit set occurs during harvest of the previous crop
Corn, grain	From tasseling through silk stage and kernels become firm	Needs adequate moisture from germination until kernel dent stage for maximum production. Depletion of 80% or more of AWC can occur during final ripening period without impacting yield
Corn, silage	From tasseling through silk stage and kernels become firm	Needs adequate moisture from germination until kernel dent stage for maximum production
Corn, sweet	From tasseling through silk stage and until kernels become firm	
Cotton	First blossom through boll maturing stage	Any moisture stress, even temporary, ceases blossom formation and boll set for at least 15 days after moisture again becomes available
Cranberries	Blossom through fruit sizing	
Fruit trees	During the initiation and early development period of flower buds, the flowering and fruit setting period (may be the previous year), the fruit growing and enlarging period, and the pre-harvest period	Stone fruits are especially sensitive to moisture stress during last two weeks before harvest
Grain, small	During boot, bloom, milk stage, early head development and early ripening stages	Critical period for malting barley is at soft dough stage to maintain a quality kernel
Grapes	All growth periods, especially during fruit filling	See vine crops
Peanuts	Full Season	
Lettuce	Head enlargement to harvest	Water shortage results in a sour and strong lettuce
Melons	Blossom through harvest	
Milo	Secondary rooting and tillering to boot stage, heading, flowering, and grain formation through filling	
Onions, dry	During bulb formation, near harvest	
Onions, green	Blossom through harvest stress	Strong and hot onions can result from moisture
Nut trees	During flower initiation period, fruit set, and mid-season growth	Pre-harvest period is not critical because nuts form during mid-season period
Pasture	During establishment and boot stage to head formation	

Table 504–2 Critical periods for plant moisture stress—continued

Crop	Critical period	Comments
Peas, dry	At start of flowering and when pods are swelling	
Peas, green	Blossom through harvest	
Peppers	At flowering stage and when peppers are swelling	
Potato	Flowering and tuber formation to harvest	Low-quality tubers result if moisture stress during tuber development and growth
Radish	During period of root enlargement	Hot radishes can be the result of moisture stress
Sunflower	Flowering to seed development	
Sorghum, grain	Secondary rooting and tillering to boot stage, heading, flowering, and grain formation through filling	
Soybeans	Flowering and fruiting stage	
Strawberries	Fruit development through harvest	
Sugar beets	At time of plant emergence, following thinning, and 1 month after emergence	Temporary leaf wilt on hot days is common even with adequate soil water content
Sugarcane	During period of maximum vegetative growth	
Tobacco	Knee high to blossoming	
Tomatoes	When flowers are forming, fruit is setting, and fruits are rapidly enlarging	
Turnips	When size of edible root increases rapidly up to harvest	Strong tasting turnips can be the result of moisture stress
Vine crops	Blossom through harvest	
Watermelon	Blossom through harvest	

Figure 504–3 A typical diagram of how soil water is extracted



and timing of irrigation applications affects root density and distribution with depth. For example, under high frequency irrigation (i.e. center pivot sprinkler systems) crops expected to have a 4 foot rooting depth in uniform soil might only extract water to depths of 18 to 24 inches in the profile, if water is applied too soon after the previous application.

Table 504–3 shows typical rooting depths for various crops on a deep, well-drained soil with good water and soil management. With good soil management and growing conditions, crops can root deeper into the soil profile.

The rooting depth of annual plants varies by stage of growth and must be considered in determining the amount of soil water available.

For most crops and forages, the concentration of moisture absorbing roots is greatest in the upper portion of the root zone. This means that, typically 70 to 80 percent of a crops water uptake will be from the top half of the rooting depth. The upper zone is the area of the most favorable conditions of aeration, biological activity, temperature, and nutrient availability. Water also evaporates from the upper few inches of soil. Therefore, water diminishes most rapidly from the upper portion of the soil. This creates a high soil-water potential gradient. In uniform soils that are at field capacity, plants use water rapidly from the upper part of the root zone and more slowly from the lower parts. About 70 percent of available soil water comes from the upper half of a uniform soil profile. Any layer or area within the root zone that has a low AWC or increased bulk density affects root development and may be the controlling factor for soil moisture availability.

Variations and inclusions are in most soil map units, thus uniformity should not be assumed. Field investigation is required to confirm or determine onsite soil characteristics. Unlike texture, structure and condition of the surface soil can be changed with management.

Very thin tillage pans can restrict root development in an otherwise homogenous soil. Never assume a plant

Table 504–3 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 for 80% of the roots)

Crop	Depth (ft)	Crop	Depth (ft)	Crop	Depth (ft)	Crop	Depth (ft)
Alfalfa	5	Clover, Ladino	2–3	Milo	2–4	Sudan grass	3–4
Asparagus	5	Cranberries	1	Mustard	2	Sugar beets	4–5
Bananas	5	Corn, sweet	2–3	Onions	1–2	Sugarcane	4–5
Beans, dry	2–3	Corn, grain	3–4	Parsnips	2–3	Sunflower	4–5
Beans, green	2–3	Corn, seed	3–4	Peanuts	2–3	Tobacco	3–4
Beets, table	2–3	Corn, silage	3–4	Peas	2–3	Tomato	3
Broccoli	2	Cotton	4–5	Peppers	1–2	Turnips	2–3
Berries, blue	4–5	Cucumber	1–2	Potatoes, Irish	2–3	Watermelon	3–4
Berries, cane	4–5	Eggplant	2	Potatoes, sweet	2–3	Wheat	4
Brussels sprouts	2	Garlic	1–2	Pumpkins	3–4	**Trees**	
Cabbage	2	Grains & flax	3–4	Radishes	1		
Cantaloupes	3	Grapes	5	Safflower	4	Fruit	4–5
Carrots	2	Grass pasture/hay	2–4	Sorghum	4	Citrus	3–4
Cauliflower	2	Grass seed	3–4	Spinach	1–2	Nut	4–5
Celery	1–2	Lettuce	1–2	Squash	3–4		
Chard	1–2	Melons	2–3	Strawberries	1–2		

root zone. Observe root development of present or former crops.

Numerous soil factors may limit the plant's genetic capabilities for root development. The most important factors are:

- soil density and pore size or configuration
- depth to restrictive or confining layers
- soil-water status
- soil aeration
- nutrient availability
- water table
- salt concentrations
- soil-borne organisms that damage or destroy plant root system

Root penetration can be extremely limited into dry soil, a water table, bedrock, high salt concentration zones, equipment and tillage compaction layers, and dense fine texture soils, and hardpans. When root development is restricted, it reduces plant available soil-water use and consequent storage, which in turn limits crop production.

High soil densities that can result from tillage and farm equipment seriously affect root penetration. Severe compacted layers can result from heavy farm equipment, tillage during higher soil moisture level periods, and from the total number of operations during the crop growing season. In many medium to fine textured soils, a compacted layer at a uniform tillage depth causes roots to be confined above the compacted layer at depths usually less than 6 to 10 inches from the surface. Roots seek the path of least resistance, thus do not penetrate a compacted dense layer except through cracks. Every tillage operation causes some compaction.

Even very thin tillage pans restrict root development and can confine roots to a shallow depth, thereby limiting the depth for water extraction. This is probably most common with row crops where many field operations occur and with hayland when soils are at high moisture levels during harvest.

Subsoiling or deep tillage when the soil is dry can fracture compacted layers. However, unless the cause of compaction (typically tillage equipment itself), the number of operations, and the method and timing of the equipment's use are changed, compaction layers will again develop. Only those field operations essential to successfully growing a crop should be used. Extra field operations require extra energy (tractor fuel), labor, and cost because of the additional wear and tear on equipment. Necessary tillage operations should only be performed when the soil surface from 0 to 2 inches or 0 to 3 inches in depth is dry enough not to cause soil smearing or compaction. The lightest equipment with the fewest operations necessary to do the job should

504.05 Tillage systems effect on water conservation

Tillage systems are an important part of sustainable agricultural systems. Tillage systems have evolved over time. Generally speaking, conservation tillage includes a variety of techniques and methods including such systems as no till, ridge till, mulch till, and minimum till. These all involve some form of residue management and only partial soil inversion. Basically, conservation tillage is any system of cultivation that reduces soil or water loss when compared to conventional systems, such as moldboard plowing which turns over the soil completely.

Conservation tillage is designed to conserve soil, water, energy, and protect water quality. Conventional tillage exposes the soil to the erosive actions of wind and water. Conservation tillage systems use residue to buffer the raindrops' energy, so water has less of an erosive force. Protection by residue, along with associated physical factors of conservation tillage, facilitates water infiltration and decreases runoff.

(a) Water conservation under residue management systems.

Tillage practices influence soil moisture throughout the growing season. Reduced and no-till systems that manage residue on the soil surface decrease evaporation losses. Both surface roughness and residue slow water runoff which allows more time for water infiltration. In addition, surface residue prevents soil surface sealing, thus increasing infiltration and the amount of soil water stored. The net effect of tillage systems that leave surface residue is less variation in soil water during the summer months and more plant available water.

The increase in soil moisture, brought on by residue management, improves microbial activity as well, which will, in turn, improve soil organic matter over time.

Evaporation is a primary source of water loss during the first half of the growing season before the crop canopy closes. Crop residue on the soil surface shades the soil surface and reduces the amount of solar energy absorbed, thereby reducing soil temperatures, and evaporation. Residue also reduces air velocity at the soil surface, slowing the rate at which evaporation occurs. Residue cover offers the greatest reduction in evaporation when the soil is moist and not yet shaded by the crop.

The difference in cumulative evaporation between bare soil and soil with a residue cover is related to the frequency and amount of rainfall. For small, infrequent rainfall events, the soil surfaces from conventional and conservation tillage show little difference in cumulative evaporation. However, with larger more frequent rains, less evaporation occurs from soil protected by surface residue than from bare soil. In stubble covered wheat field, evaporation ranges from 60 to 75 percent of that occurring from bare soil. Evaporation from the soil depends on water rising to the surface by capillary action as the soil dries. Shallow incorporation of residue reduces this capillary action however; leaving residue on the soil surface generally reduces evaporation more than shallow incorporation.

Water infiltration is the process of water entering the soil at the soil/air interface. Crop residue affects soil infiltration by intercepting raindrop energy and the associated soil sealing or ponding that occurs thereby increasing infiltration and reducing the amount of runoff. Simulated rainfall studies in Ohio show that infiltration increases with surface residue (table 504–4).

Runoff tillage systems that leave crop residue on the soil surface generally reduce runoff. The factors that influence the differences in runoff are soil characteristics, weather patterns, the presence of macro pores, management, and the amount, kind, and orientation of residue. The residue characteristics that affect water infiltration also affect runoff by increasing the time to initiation of runoff and lowering runoff rates. Residue on the soil surface increases the surface roughness of the soil, reduces runoff velocities, and causes ponding that further delays runoff. In addition, surface residue obstructs and diverts runoff, increasing the length of time in the down slope flow path allowing more time for infiltration.

Another important point is the effect of having both standing and flat residues present. The presence of standing and flat residues reduces the likelihood that small localized flow areas will combine into larger networks, and decreases the velocity and overall transport of runoff from the field. If the climate and soil conditions exclude macro pore development and traffic causes unrelieved reductions in infiltration, runoff rates can increase even with high residue crop production systems such as no-till, particularly in the early years of the systems before surface organic matter has time to accumulate.

Snow catch—Maximizing snow catch is a vital conservation measure in the northern Great Plains, since snow constitutes 20 to 25 percent of the annual precipitation. Stubble height management and orientation are tools used to maximize snow catch. Taller stubble retains more snow, increasing soil water content. Bauer and Black (1990) in a 12 year study reported that increasing small grain stubble height from 2 to 15 inches increased soil water content to a depth of 5 feet by 1.6 inches. In addition to stubble height, scal-

Table 504–4 Effect of tillage and corn residue on infiltration using simulated rainfall (Triplett et al. 1968)

Total infiltration after 1 hour (inches)		
Treatment	**Initial run**	**Wet run 1/**
Plowed, bare	0.71	0.41
No-tillage, bare 2/	0.48	0.25
No-tillage, 40% cover	0.92	0.53
No-tillage, 80% cover	1.73	1.37

1/ Wet run took place 24 hr after initial run.

2/ Residue cover was removed for research purposes.

loping the stubble (varying the height of stubble with each pass) increases the amount of snow trapped by the stubble. Increasing the snow catch on a field may increase spring melt runoff depending on the early spring soil infiltration characteristics. However, in soils on which annual crops are grown, infiltration of snowmelt occurs without runoff due to the soil being frozen while dry or not frozen as deeply due to the snow coverage to permit infiltration. Greb (1979) reported that the efficiency of storing meltwater is often double that of storing water received as rain.

Water storage—Soil moisture savings is of great importance in regions of low rainfall and high evaporation, on soils low in water holding capacity, and in years with below normal rainfall. In some regions, for example the Corn Belt, excessive soil moisture in the spring months may have potential negative effects on crop growth since it slows soil warming and delays planting. However, having more available water during crop pollination and seed filling usually offsets these early season negative effects. Seed zone soil moisture also aids in plant establishment and growth in dry areas of the United States. For a high percentage of the farmland, moisture savings is one of the primary reasons producers consider conservation tillage systems.

Research on the effects of reducing tillage and increasing surface residue have indicated that high amounts of surface residue result in increased soil water stored. Unger (1978) reported that high wheat residue levels resulted in increased water storage during the fallow period and the increased subsequent grain sorghum yields the following year. Similar results of water storage under high residue conditions are shown in table 504–5, summarized by Greb (1983), for 20 crop years from four locations.

Management changes in the Great Plains since 1916 have improved soil water storage, fallow efficiency (percentage of the precipitation received during the fallow period and stored as soil water), and small grain yields. However, fallow efficiencies up to 40 percent were reported in the 1970s and have not improved beyond this value due to the fact (during subsequent research) that a majority of soil moisture recharge is stored early in the year, the time of year directly after harvest operations in the fall up through spring. Very little soil water is stored after that time; in fact, moisture is lost after that time due to evaporation if the soil surface is left unprotected. This indicates that reducing or eliminating fallow from the rotation, intensifying the cropping pattern, and utilizing the soil moisture stored through the rotation, is a means of taking advantage of our increased capability to store water earlier in the cropping cycle with high residue crop production systems.

Excessive soil water—Tillage practices and crop residue management in annual cropping systems play an important role in how soil receives and retains moisture. On perennial crops, such as alfalfa, residue management is not normally a concern as fields are tilled and re-seeded at intervals that are usually 5 years or greater, but annual crops may require some annual tillage.

Tillage practices and crop residue management affect the way water moves into and off of the soil (infiltration and runoff), as well as the way water moves from the soil into the atmosphere evaporation). Especially during drought periods, efficient use of limited water is important.

Management of residues from a previous crop can have significant effect on water movement (including runoff leading to erosion) and the evaporation from the soil surface. Runoff potential exists when precipitation or the rate of irrigation exceeds the infiltration rate of the soil.

Table 504–5 Net soil-water gain at the end of fallow as influenced by straw mulch rates at four Great Plains locations

Location	Years reported	Mulch rate (mg/ha)			
		0	**2.2**	**4.4**	**6.6**
Bushland, TX	3	7.1	9.9	9.9	10.7
Akron, CO	6	13.6	15.0	16.5	18.5
North Platte, NE	7	16.5	19.3	21.6	23.4
Sidney, MT	4	5.3	6.9	9.4	10.2
Mean		10.7	12.7	14.5	15.7
Gain with mulch			2.0	3.8	5.0

Note: Soil water gain units = centimeter

Even low pressure irrigation systems, as may be used on some center pivots, may exceed the infiltration rate of the soil. The presence of crop residues can increase the infiltration rate and decrease the potential for runoff by creating an uneven surface that slows the movement of water.

Runoff can also increase if the soil infiltration rate is reduced over time. A number of factors such as soil texture and structure, excessive surface tillage, and water application or precipitation can cause a reduction in infiltration. As the size and number of water droplets increases, fine soil particles are consolidated on the surface to form a thin crust which reduces infiltration. Soil crusts can reduce infiltration rates up to 75 percent.

One way to combat the negative effects of water droplets is to ensure that crop residues are evenly distributed over the soil surface. Crop residues spread in this manner protect the soil by absorbing energy carried by the falling water droplets. This limits soil crust development, resulting in a more consistent infiltration rate throughout the growing season.

Crop residue on the soil surface reduces evaporation. Most evaporation occurs when the soil is wet. Residue insulates the wet soil from solar energy and reduces evaporation. When the soil is wet more often, as can occur with irrigation, evaporation increases, and the effect of crop residue is even more important in reducing water losses to evaporation. This also demonstrates why irrigating less often, with more volume per application, is more efficient than frequent, light irrigations, which more frequently wet the soil surface. Crop canopies also play a role in reducing evaporation by shading the soil surface.

A study in Nebraska showed that crop residue (6 tons of wheat straw per acre) in an irrigated corn crop reduced evaporation by 2 to 2.5 inches during the growing season. Even lower levels of residue can have a significant impact on reducing evaporation.

Use conservation practices that increase water infiltration and minimize water loss:

- protect the soil surface with plants, cover crops, mulches, and residues
- use buffers to capture snow melt, reduce runoff, and prevent erosion
- use manure, cover crops, and crop residues to increase soil organic matter and build soil quality

To achieve these benefits use cropping practices such as:

- rotations with perennial crops such as grasses and alfalfa
- minimum tillage or no-till to reduce evaporation losses

Soil properties that affect water infiltration, permeability, and drainage must always be properly assessed when making residue management decisions. Research in the Corn Belt has shown that no-till management systems on some poorly drained soils has resulted in lower yields compared to the yields of conventionally tilled systems. Continued research has shown, however, that after 18 years of continued no-till that yields are now equal or greater than conventionally tilled systems. The initial yield reductions on these poorly drained soils may have been attributed to a number of different factors. The positive yield response after continuous no-till on these soils may be attributed to factors including the development of internal drainage characteristics such macropores, increases in organic matter and microbial activity, better soil structure, and the use of disease resistant cultivars.

When dealing with heavier residue amounts from a proceeding crop it may be necessary in no-till or even mulch-till situations to use residue managers that move the residue to the side of the seed trench. Poorly drained soils are not easily adapted to high residue systems and may need to be managed with limited till systems such as ridge-till or fall and spring strip-till methods. Some warm-season species such as corn or sunflower respond to warmer, clean seedbed conditions. This may also be accomplished by including crops in the rotation that produce lower amounts of dark colored residue or including cover crops. Refer to Subpart 506B, Suitability for crop production systems.

Excess water, which can be caused by over irrigation, under utilization of excess soil moisture, improper crop rotations, or excess precipitation, can cause another major resource issue, namely salinization. When excess soil moisture goes unused, it will either evaporate at the soil surface or percolate through the root zone. In arid and semi-arid regions, percolated moisture will often move laterally along an impermeable layer beneath the root zone until it finds its way to the surface where it evaporates. After several years, salt accumulations on the soil surface become elevated enough to become toxic to crops and forages.

Additionally, if irrigation water has even slightly elevated dissolved salts dissolved, salt concentrations will, over time, increase. If concentrations increase enough, it will negatively affect crop and forage production. More discussion on salinization can be found in section 504.06.

Pests—Changes from conventional tillage systems to conservation tillage systems will most likely also change some aspects of pest management. For pathogens, such as fungal and bacterial pathogens, conventional tillage buries crop residue which can destroy many of these pathogens. Many pathogens use surface residue for overwintering, but are then controlled when they are buried. The use of conservation tillage, because of this factor, may cause increases in severity of some diseases and insect populations can increase, requiring more or different controls.

Rather than increasing chemical pest control, an intensive crop rotation will assist in mitigating pest issues. Additionally, integrated pest management systems may need to be adopted at the same time that tillage systems that utilize greater amounts of surface residue are utilized.

(b) Cropping system intensity

Improving the relative water use efficiency in crop production systems is a key goal in achieving sustainable cropping systems. Reducing water losses in cropping systems by changes in tillage, residue management, crop selection, irrigation water management, and crop sequence result in more diverse and intense rotations and greater water use efficiency (WUE).

Historically, crop rotations were much more diverse than they are presently. The loss of crop rotation diversity can be attributed to many factors including economics, farm programs, mechanization, technology, the development of commercial fertilizer, pesticides, and specialization in livestock production leading to fewer cattle operations.

An intense crop rotation can also improve soil health and have a positive effect on the whole farm by reducing weeds and insect infestations and resistance, spreading workloads, diversifying income and spreading weather risks.

The ability of a crop to produce to the physical and chemical limits of the cropping system is largely related to the health of the root system. The health of the root system, in turn, is directly related to the length of the crop rotation, ideally up to 3 or possibly 4 years or more.

The yield of all crops has long been known to decline with monoculture to some level significantly below the original yield of the same crop grown in some rotation system. In many cases this decline can be attributed to root disease and hence loss of absorptive capacity of the root system because of increasing populations of root pathogens.

Any cropping system, rotation or monoculture, depletes the soil of nutrients, starting with nitrogen and then eventually phosphorus, sulfur, potassium, trace elements, and others. Organic matter content of the soil is also reduced as nutrients are mined from the soil. Organic matter is a natural form of slow-release fertilizer for plant growth and it provides the glue or supports the microorganisms that provide the glue for the aggregate structure essential for soil aeration, soil and water conservation, and healthy roots.

Alternating crops that result in an intense, diversified cropping system allows time for the natural soil microbes to displace or destroy root pathogens and other pests of any one crop enabling maximum production while maintaining soil health.

Changes in cropping systems by decreasing tillage, increasing surface residues, making conscious decisions on residue orientation, as well as, strategically placing crops in rotations have produced positive changes in water use efficiency. Cropping system intensification has improved the water use efficiency (WUE), and has increased the productivity of crop production systems.

Continuous cropping may be a viable option for producers in areas where fallow has traditionally been a part of a cropping sequence. With high residue management the inclusion of annual forages, such as sorghums, millet, field peas, or small grains, increase the producers flexibility to maximize WUE. Crop choice affects WUE of the crop production system because each species has a different potential for production.

Several predictive tools (water-use-production functions) have been developed to assist producers in crop selection in several environments across the Great Plains. Black et al. (1981) suggested that a flexible cropping strategy would provide efficient water use to control saline seeps in the northern Great Plains.

Flexible cropping—Flexible cropping is defined as seeding a crop when stored soil water and rainfall probabilities are favorable for satisfactory yield, or fallowing only when prospects are unfavorable. Available soil water can be estimated by measuring moist soil depth with a soil moisture probe or other soil sampling equipment. Brown et al. (1981) have developed soil water guidelines and precipitation probabilities for barley and spring wheat for flexible cropping systems in Montana and North Dakota.

When considering a flexible cropping system a producer should evaluate the amount of plant-available soil water at seeding time, the precipitation probabilities for the seasonal needs of a given crop, and management factors such as variety, crop rotation, weed and insect problems, soil fertility, and planting date.

Current information in the Great Plains at various locations includes yield water-use-production functions for winter wheat, spring wheat, barley, oats, millet, corn, sunflower, dry beans, canola, crambe, soybean, and safflower given soil moisture and rainfall-probability information (Brown and Carlson 1990; Vigil et al. 1995; Nielson 1995). This information can assist a producer in crop selection in a given year; however users of these water use/yield relationships need to understand that the final crop yield is influenced by the timing of precipitation as well as the amount of water used.

Another tool was designed by the Dakota Lakes Research Farm in South Dakota. The Crop Intensity and Diversity Index can be used to assist the development of appropriate alternative rotations. The tool assigns relative values to crops within a rotation depending upon differing characteristics in terms of their impacts on various aspects of crop production used in a given environment by a particular producer.

Irrigation effects—Tillage practices and crop residue management affect the way water moves into and off of the soil (infiltration and runoff), as well as the way water moves from the soil into the atmosphere (evaporation).

Under sprinkler irrigation systems, management of residues from the previous crop can have significant effect on water movement (including runoff leading to erosion) and evaporation from the soil surface. Runoff potential exists when the rate of irrigation exceeds the infiltration rate of the soil.

Low pressure irrigation systems, as may be used on some center pivots, may also exceed the infiltration rate of the soil. The presence of crop residues can increase infiltration rate and decrease the potential for runoff by creating an uneven surface that slows the movement of water. There are certain tillage operations and other management practices that also may affect the movement of water including the use of the dammer-diker implement or farming on the contour.

Runoff can also increase if the soil infiltration rate is reduced over time. Factors such as soil texture and structure, excessive tillage, and water application can cause a reduction in infiltration. As the size and number of water droplets increases, fine soil particles are consolidated on the surface to form a thin crust which reduces infiltration. Soil crusts formed during the growing season can reduce infiltration by as much as 75 percent.

One way to combat the negative effects of water droplets is to ensure that crop residues are evenly distributed over the soil surface. Crop residue spread in this manner protects the soil by absorbing energy carried by the falling water droplets. This limits soil crust development, resulting in a more consistent infiltration rate throughout the growing season.

Crop residue on the soil surface reduces evaporation. Most evaporation occurs when the soil is wet. Residue insulates the wet soil from solar energy and reduces evaporation.

When the soil is wet more often, as occurs with irrigation, evaporation increases, and the effect of crop residue is even more important in reducing water losses. This also demonstrates why irrigating less often, with more water volume per application, is more efficient than frequent than frequent, light irrigations, which more frequently wet the soil surface. Crop canopies also play a role in reducing evaporation by shading the soil.

A study in Nebraska showed that crop residue (6 tons per acre) reduced evaporation by 2 to 2.5 inches during the growing season. However, even lower levels of residue can have a significant role in reducing evaporation.

Conservation practices that increase water infiltration and minimize water loss are:

- protect soil with plants, cover crops, mulches, and residues
- use buffers to capture snow melt, reduce runoff, and prevent erosion
- use manure, cover crops, and crop residues to increase organic matter and build soil quality
- rotate with perennial crops
- use minimum tillage or no-till

504.06 Saline Seeps

(a) Development of saline seeps

Saline seep describes a salinization process accelerated by dryland farming practices. Saline seep is an intermittent or continuous saline water discharge at or near the soil surface downslope from a recharge area under dryland farming conditions that reduces or eliminates crop growth in the affected area because of increased soluble salt concentration in the root zone. Saline seeps are differentiated from other saline soil conditions by their recent and local origin, saturated root zone in the soil profile, shallow perched water table, and sensitivity to precipitation and cropping systems. In the recharge area, water percolates to zones of low hydrologic conductivity at depths of 2 to 60 feet below the soil surface and flows internally downslope to emerge at the point where the transport layer approaches the soil surface or soil permeability is reduced.

The saline-seep problem stems from surface geology, above-normal precipitation periods, and farming practices that allow water to move beyond the root zone. Under native vegetation, grasses and forbs used most of the water before it had a chance to percolate below the root zone to the water table. With sod plow-up, subsoil became wetter and fallow kept the land relatively free of vegetation for months at a time. Beginning in the forties, soil water storage efficiency during fallow improved with the advent of large tractors, good tillage equipment, effective herbicides, and timely tillage operations. This extra water filled the root zone to field capacity and allowed some water to move to the water table and downslope to emerge as a saline seep.

Several factors that may individually or in combination contribute water to shallow water table include: fallow, high precipitation periods, poor surface drainage, gravelly and sandy soils, drainageways, constructed ponds and dugouts, snow accumulation, roadways across natural drainageways, artesian water, and crop failures resulting in low use of stored soil water. Saline-seep formation begins with a root zone filled to its water-holding capacity. Some of this water runs off the surface, some evaporates, and the rest moves into the soil. Once the soil is filled to field capacity, any additional water that moves through the root zone may contribute to saline seepage.

Water percolating through salt-laden strata dissolves salts and eventually forms a saline water table above an impermeable or slowly permeable layer. The underground saline water moves downslope and dissolves more salts, adding to the perched water table at the site of the seep. Whenever, the water table rises to within 3 feet of the surface the water plus dissolved salts then move to the soil surface by capillary action were the discharge water evaporates, concentrating salt on or near the soil surface. As a result, crop growth in the affected area is reduced or eliminated and the soil is too wet to be farmed.

(b) Identification of saline seeps

Early detection and diagnosis of a saline-seep problem are important in designing and implementing control and reclamation practices to prevent further damage. By early detection, a producer may be able to change his or her cropping system to minimize the damage. Detection of discharge areas may be accomplished by visual or by electrical conductivity detection. Visual symptoms of an impending saline seep may include:

- vigorous growth of kochia or foxtail barley in small areas where the soil would normally be too dry to support weed growth
- scattered salt crystals on the soil surface
- prolonged periods of soil surface wetness in small areas
- poor seed germination or rank wheat or barley growth
- accompanied by lodging in localized areas
- stunted trees in a shelterbelt accompanied by leaf chlorosis
- a sloughed hillside in native vegetation adjacent to a cultivated field

Soil electrical conductivity (EC), which is proportional to soil salinity, can be determined in the field using resistivity. This technique can be used to identify and confirm an encroaching or developing saline seep. Soil salinity in the discharge area may be low near the soil surface, but increases considerably with depth. Once the discharge area is identified, the next step is to locate the recharge area. Most remedial treatments for controlling the seep must be applied to the recharge area, which is always at a higher elevation than the discharge area. The approximate size of the recharge area must be determined to be successful. Most recharge areas are within 2,000 feet and many are within 100 to 600 feet of the discharge area, depending on the geology involved.

Several procedures for identifying the recharge area include: visual, soil probing, soil surveys, drilling, soil resistivity, and electromagnetic techniques. Even if the previously mentioned equipment is not available, a visual approximation of the recharge area can be made, and strategies implemented to correct the saline-seep problem. Some facts to remember are that the recharge areas are higher in elevation than the seep or discharge area, the recharge areas are generally within 2,000 feet of the discharge area, and that seeps in glacial till areas expand downslope, laterally, and upslope toward the recharge area. Saline seeps in non-glaciated areas tend to expand downslope, away from the discharge area. After the recharge area has been located, a management plan should be designed to control the saline-seep problem.

(c) Effects of salinity on yields

Saline soil is a term used to characterize soil containing sufficient salts to adversely affect the growth of most crop plants. One or more of the following may cause these adverse effects.

- Direct physical effects of salts in preventing soil water uptake by the plant roots because of increased osmotic tension.
- Direct chemical effects of salt in disrupting the nutritional and metabolic processes of the plant.
- Indirect effect of salt in altering soil structure, permeability, and aeration.

Agricultural crops differ significantly in their response to excessive concentrations of soluble salts in the root zone. This ability of the plant to produce economic yields in a saline environment is termed salt tolerance. Crop selection is one of the primary options available to growers to maximize productivity under saline conditions. Table 504–6 lists the salinity threshold and yield decrease of several selected agricultural crops. The threshold salinity level is the maximum allowable salinity that does not reduce yield below that of non-saline conditions. The yield decrease is reported as a percent yield reduction for every whole unit increase in salinity measured as electrical conductivity (EC) mmho/cm. For example, alfalfa yields decrease about 7.3 percent per unit of salinity increase above 2.0 mmho/cm. Therefore, at a soil salinity of 5.4 mmho/cm, alfalfa yield would be 25 percent lower than at soil salinity levels less than 2.0 mmho/cm.

Crop production has been reduced on approximately 2 million dryland acres in the northern Great Plains of the United States and Canada. Brown (1982) reported that this production loss on 2 million acres in the northern Great Plains could be translated into $120 million in lost annual farm income.

(d) Management practices for control of saline seeps

Saline-seeps are caused by water moving below the root zone in the recharge area. Because of this movement of water though the recharge area, there will be no permanent solution to the saline-seep problem unless control measures are applied to the recharge area.

These measures vary according to the soil texture and underlying geologic material, water table fluctuations, depth to the low hydraulic conductivity zone, occurrences of potholes and poorly drained areas, and annual precipitation and frequency of high precipitation periods.

Two general procedures are available for managing saline seeps: either make agronomic use of the water for crop production before it percolates below the root zone; or mechanically drain either surface or subsurface water before it reaches the discharge area. Mechanical drainage is generally not performed either because of current farm bill legislation or because of constraint that subsurface water is excessively contaminated with salts and downstream disposal is difficult because of physical or legal limitations. However, before any control measures are implemented an evaluation of the land capability class should be determined. All control measures should be compatible with the land capability class involved.

The most effective solution to the saline-seep problem is to use as much of the current precipitation as possible for crop or forage production before it percolates beyond the root zone. Forage crops, such as alfalfa, use more water than cereal grains and oil crops because they have deep root systems, are perennial, and have longer growing seasons. Planting alfalfa in the recharge area of a saline seep is often the most effective way to draw down stored subsoil moisture and stop water flow to a saline-seep. Alfalfa can use all current precipitation plus a substantial amount of water from the deep subsoil.

Halvorson and Reule (1976, 1980) found that alfalfa growing on approximately 80 percent of the recharge area effectively controlled several saline seeps. They also found that a narrow buffer strip of alfalfa (occupying less than 20 percent of the recharge area) on the immediate upslope side of a seep did not effectively control the water in the discharge area. Grasses may also effectively draw down subsurface water if the depth to the low hydraulic conductivity zone is less than 15 feet. After terminating alfalfa or grass production, the recharge area should be farmed using a flexible cropping system. Flexible cropping is defined as seeding a crop when stored soil water and rainfall probabilities are favorable for satisfactory yield or fallowing when prospects are unfavorable.

Available soil water can be estimated by measuring moist soil depth with a soil moisture probe or other soil sampling equipment. Black et al. (1981) suggested that this cropping strategy would provide efficient water use to control saline seeps in the northern Great Plains. Brown et al. (1981) have developed soil water

Table 504–6 Salt tolerance of selected crops [1/]

Common name	Botanical name	Salt tolerance threshold (mmhos/cm	Yield decline (% per mmhos/cm)
Alfalfa	*Medicago sativa*	2.0	7.3
Barley	*Hordeum vulgare*	8.0	5.0
Sorghum	*Sorghum bicolor*	6.8	16.0
Soybean	*Glycine max*	5.0	20.0
Wheat	*Triticum aestivum*	6.0	7.1
Wheatgrass, tall	*Agropyron elongatum*	7.5	4.2
Wildrye, beardless	*Leymus triticoides*	2.7	6.0

1/ Maas and Hoffman (1977) and Maas (1990) guidelines and precipitation probabilities for barley and spring wheat for flexible cropping systems in Montana and North Dakota.

After successful application of control measures to the recharge area, the seep area and surrounding area can then be seeded to a grass or grass/legume mixture tolerant to the saline conditions present in the discharge area. A return to a cropping system that does not adequately utilize stored soil water in the recharge area may reactivate the seep.

Once the water flow from the recharge area to the seep has been stopped or controlled and the water table in the seep has dropped enough to permit cultivation, cropping in the seep area can begin. Crop selection is important when initiating crop production on the discharge area. In the northern Great Plains, six-row barley is the most salinity-tolerant cereal available, and it is normally the first crop seeded. As the reclamation processes continues, comparing yields in and outside the seep area can be used to monitor progress. The water table depth should be closely monitored during the reclamation period.

Another approach that can be used on discharge areas is to manage salt-tolerant grasses seeded on the area. If the water table is above 4 feet the grasses should be mowed and completely removed to prevent excess snow accumulation and the subsequent rise in the water table. If the water table is below 4 feet, the grass can be left to catch snow. The resulting snowmelt will leach the salt downward into the soil and improve subsequent grass growth. Snow trapping using grass strips or crop stubble will enhance water movement through the profile in the discharge area and hasten the reclamation process.

These practices will not be effective until hydrologic control is achieved in the recharge area and the water table is significantly lowered in the discharge area. Research and farmer experience have shown that yields will generally return to normal in 3 to 5 years.

In saline-seep areas, observation wells are useful for monitoring water table levels during the control, reclamation, and post-reclamation periods. Water tables fluctuate seasonally and annually. Reclaimed saline seeps may be reactivated by a significant rise in the water table, which persists for several weeks or months. If a saline water table is less than 3 feet below the soil surface, saline water can move to the surface by capillary rise and create a salt problem. To alleviate this problem, monitoring wells at least 10 feet in depth should be installed in discharge areas, along drainageways, and in recharge areas. Ideally, the water table should be at least 6 feet in depth. Water table levels should be monitored monthly, especially during and after snowmelt, and rainy seasons. A rising water table that persists into the summer months indicates that cropping practices should be intensified to increase soil water use.

504.07 Irrigation related agricultural salt problems

The major solutes comprising dissolved salts are the cations (sodium, calcium, magnesium, and potassium) and the anions (sulfate, chloride, bicarbonate, carbonate, and nitrate). Dissolved minerals might also include other constituents including manganese, boron, lithium, fluoride, barium, strontium, aluminum, rubidium, and silica.

Irrigation can bring about the salinization of soils and waters and the subsequent threat to the sustainability of irrigated agroecosystems. Over the course of history, thriving civilizations declined in part due to their inability to sustain food production on lands that had been salinized. Worldwide, the trend of decreasing crop production capacity, attributed to soil degradation and the effects of salinity continues. It has been estimated that in the United States yield reductions due to salinity and associated waterlogging occur on an estimated 30% of all irrigated land.

There are three principles regarding irrigation and salinity that are important to understand;

- all waters used for irrigation contain salts of some kind in some varying amount
- salinization of soil and water is inevitable to some extent
- irrigated agroecosystems cannot be sustained without drainage, either natural or artificial

The primary origin of salts in the hydrosphere and soils is from two sources; a broad category that called hydrogeological and the second category that describes the contributing processes of human activities as anthropogenic.

As an anthropogenic source of salinity, irrigation has a profound effect on introducing soluble salts into irrigated agroecosystems that is driven by plant communities (crops/forage) and climate factors associated directly with evapotranspiration and compounded by the excessive application of water. The causes contributing to the excessive application of water are inefficient irrigation distribution systems, poor on-farm management practices, and inappropriate management of drainage water.

Application of irrigation water

Application of irrigation water results in the addition of soluble salts. The primary soluble salt constituents of interest are sodium, calcium, magnesium, potassium, sulfate, and chloride dissolved from geologic materials with which the waters have been in contact and alkalinity, i.e. bicarbonate and carbonate, principally from atmospheric and soil zone dissolution of carbon dioxide. Therefore, water quality needs to be evaluated in terms of assessing the combined effects of salinity, infiltration/permeability (sodicity), and nutritional imbalance/toxicity.

Salinity
Sometimes called evapo-concentration, the concentrations of soluble salts increase in soils as the soil water is removed to meet its atmospheric demand by evaporation and transpiration. The salts, which are left behind concentrate in the shrinking soil-water volume with each successive applied irrigation. This adverse effect of soil solution salinity is the reduction of transpiration at a threshold where biochemical energy is diverted away from dry matter production which suppresses yield once the average root zone soil salinity exceeds the crop dependent threshold value unless adequate leaching and drainage are provided. This illustrates another important principle that for soils that have reached cation exchange equilibrium that the salt load (i.e. volume x concentration) of the soil profile where water is being consumed by plants is solely dependent upon the salt load of the infiltrating water volume and the salt burden of the root zone outfall water volume as represented by the leaching fraction.

Not all crop plants respond to salinity in the same way. Some produce acceptable yields at higher soil salinity levels than others. Each crop species has an inherent ability to make the needed osmotic adjustments enabling them to extract more water from a saline soil. This ability for some crops to adjust to salinity is extremely useful. In areas where the accumulation of salinity within the soil profile cannot be controlled at acceptable levels, an alternative crop can be selected that is more tolerant resulting in the production of better economical yields.

Infiltration/permeability problems
Although crop yield is primarily limited by EC level of the irrigation water, the application of irrigation water with a sodium imbalance can further reduce yield under certain soil texture conditions. Generally, high salinity water increases infiltration, low salinity water decreases infiltration, and water with a high sodium content relative to the calcium and magnesium content decrease infiltration. This latter potential adverse effect of certain natural waters on soils is the soil property termed “sodicity.”

Managing the impacts of irrigated-related salt problems.

There is usually not one single prescription for an effective salinity management strategy. Rather, different practices and approaches need to be combined into a management scheme that satisfactorily addresses an existing salinity problem or preventing one from manifesting itself into the irrigated ecosystem.

There are seven requisite management elements or objectives in formulating a comprehensive management strategy. These essential elements are:

- assess the source of irrigation water for its suitability
- deliver irrigation water to fields efficiently
- apply irrigation water to fields in an efficient manner that minimizes the leaching fraction and resulting minimized deep percolation
- provide adequate drainage
- use planting and tillage procedures that prevent excessive salinity accumulation
- know your cropping and soil limitations
- monitor irrigation adequacy and soil profile salinity

Assess the suitability of irrigation water sources.
In order to develop the most effective salinity control strategy for a given situation, evaluation of a given source of water must be considered.

A complete inventory of the necessary parameters is essential to support the criteria to be used in judging suitability that create adverse soil conditions to crop use. The established criteria of a water suitability have already been discussed; namely salinity, sodicity, and, toxicity.

Deliver irrigation water to fields efficiently.
For conveyance of irrigation and drainage waters to and away from the points of application, seepage losses must be minimized. Controlling seepage losses and maintaining drainage systems are critical. Excessive loss of irrigation water from canals constructed in permeable soil contributes to not only the mineral dissolution of the underlying geologic materials, but contributes significantly to the manifesting of high water tables and soil salinization. Poor drainage system maintenance potentially impedes flow of drainage waters that also contributes to high water table hazards and additional soil salinization.

Apply irrigation water in a manner that minimizes leaching and deep percolation.
Another keystone principle is that Irrigation water management is not a product, but a process of determining and controlling the volume, frequency, and application rate of irrigation water in a planned, efficient manner.

It is the soluble salts that, if not managed in the soil profile, will eventually build up to the point that crop yields are adversely affected. Leaching, as the key factor in controlling the soluble salts, is accomplished by applying an amount of water that is in excess of the crops seasonal evapotranspiration and runoff. Too little leaching results in excessive soil profile accumulation while too much leaching contributes to the probable excessive percolation of groundwater into underlying geological formations that can result in additional salt dissolution. This in turn increases the salt loading of alluvial water sources and sometimes further degradation of downstream aquifers that contributes to regional salinization.

Provide adequate drainage.
Inappropriate management of drainage water exasperates the potential salinity hazards from excessive use of water. In order to provide an adequate salt balance within the root zone the flux of water must be in the downward direction so as to remove salts by leaching. Therefore, there must not be any marked upward flux of water such that which occurs from shallow water tables along with additional salts transported into the vadose zone.

Steps must be taken to ensure that the necessary minimum depth to water table is provided so that the continuous downward flux of both water and salts is maintained. The resulting drainage must then be discharged either naturally or artificially. Where drainage waters are discharged through artificial engineered systems of subsurface and surface drains from irrigated regions, it is important that drainage waters from shallow water tables be intercepted, collected, and then subsequently returned to open water bodies as quickly as possible; be reused; or transported to an appropriate disposal site.

Know your cropping and soil limitations and grow suitable salt tolerant crops.
Strategies for managing irrigation-related agricultural salt problems include the exhaustion of the consumptive use capacity of water. The goal is for the crop to consume the maximum amount of water by transpiration so as to accumulate the greatest amount of dry matter. This applies to the use of low-salinity water as well as with high salinity water sources or drainage water for crops that are sufficiently salt-tolerant.

Salt tolerance of crops not only differs considerably but also differs phonologically in that there are certain stages of growth where crops become more tolerant. This leads to greater attention given to developing crop rotations that offer opportunities of using poor quality water separately or sequentially.

Use planting and tillage procedures that prevent excessive salinity accumulation.
As a general rule most plants are salt tolerant during germination. After germination, plants become sensitive during emergence and development of the seedling. Stand losses can occur when planting configurations allow salt accumulation progressively towards the surface and center of raised beds or ridges, par-

ticularly in regions of the seedbed where water flows converge and subsequently evaporate.

Monitor irrigation adequacy and soil profile salinity.
Fundamental to the planning process are the inventory and collection of necessary natural resource information and the evaluation of the effectiveness of an implemented strategy. These are important in managing the impacts of irrigation-related agricultural salt problems and the evaluation of the strategy and continued monitoring that ensures that the objectives are being achieved.

A primary consideration in achieving a sustainable irrigated agro-ecosystem susceptible to salinity hazards soils requires knowledge of the concentration and distribution of soluble salts in the soil. This includes information on spatial and temporal trends in soil salinity status and water table depths. This can be accomplished with periodic assessments and inventories that serve as a framework to guide management decisions concerning leaching adequacy and drainage.

If the outcomes identified within this framework are to be achieved traditional observation methods are no longer appropriate. The framework requires the need for repeated measurements in both time and space that accurately describe salinity patterns. Obtaining the needed information using conventional soil sampling and laboratory analysis procedures is not usually practical and certainly cost prohibitive. One of several options of practical field salinity assessment procedures and *in situ* techniques should be considered where large intensive and extensive data sets can be collected consisting of geospatial measurement of the bulk soil electrical conductivity (EC_a) directly in the field (Rhoades, et al., 1997; Lesch, et al., 1998). The methodology and instrumental techniques can be integrated into systems that are rapid and mobile (Corwin and Lesch, 2005) provide systematic means for not only describing salinity conditions but also detailed information of various agricultural practices and management effects (Lesch, *et al.*, 2005).

504.08 References

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United States
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**Natural
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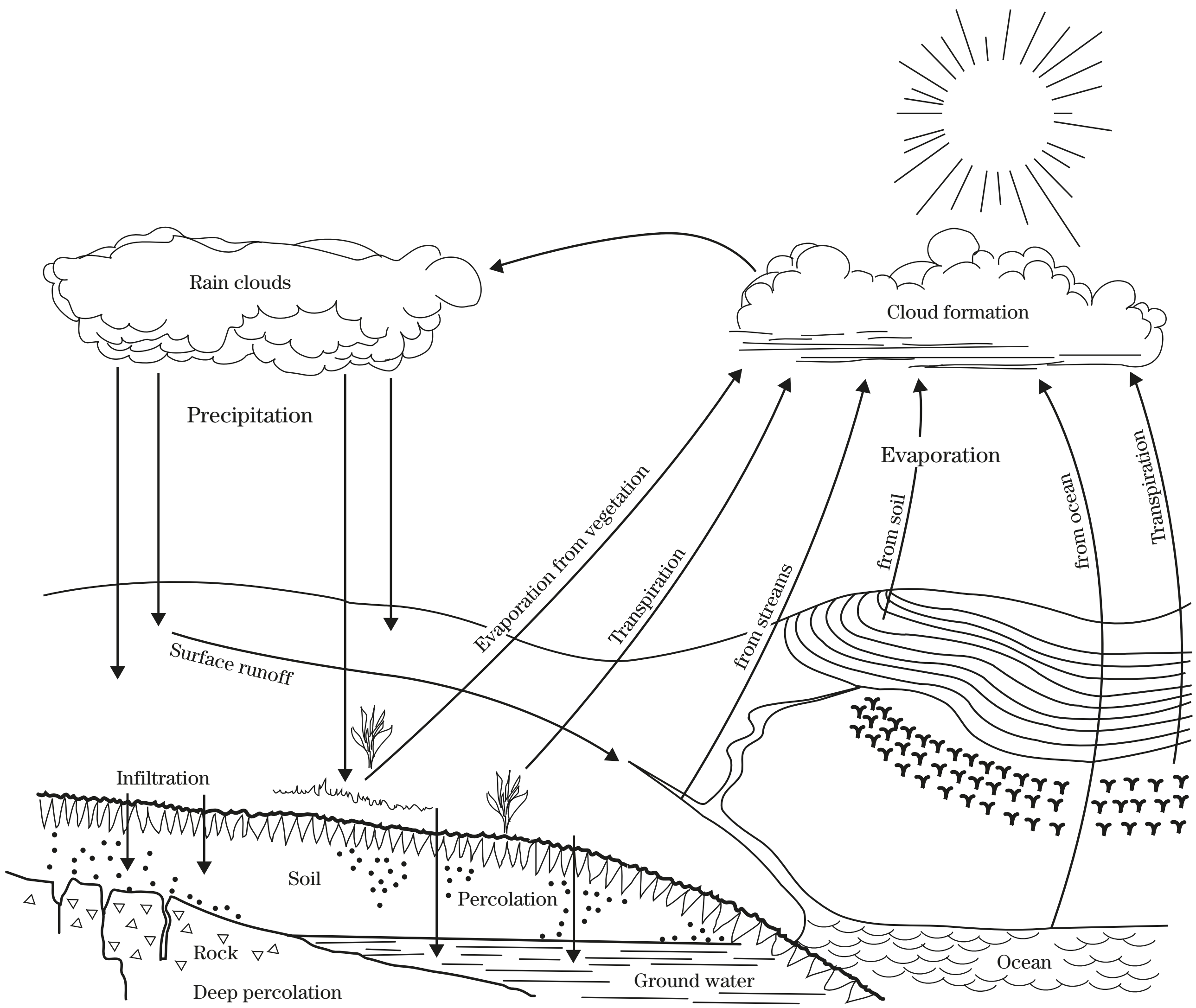
Part 630 Hydrology
National Engineering Handbook

Chapter 7 Hydrologic Soil Groups



Issued January 2009

Acknowledgments

Chapter 7 was originally prepared by **Victor Mockus** (retired) and reprinted with minor revisions in 1972. This version was prepared by the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) under guidance of **Jon Werner** (retired), NRCS; with assistance from **Donald E. Woodward** (retired), NRCS; **Robert Nielsen** (retired), NRCS; **Robert Dobos**, soil scientist, NRCS; and **Allen Hjelmfelt** (retired), Agricultural Research Service. It was finalized under the guidance of **Claudia C. Hoeft**, national hydraulic engineer.

Preface

This chapter of the National Engineering Handbook (NEH) Part 630, Hydrology, represents a multi-year collaboration between soil scientists at the National Soil Survey Center (NSSC) and engineers in the Conservation Engineering Division (CED) at National Headquarters to develop an agreed upon model for classifying hydrologic soil groups.

This chapter contains the official definitions of the various hydrologic soil groups. The National Soil Survey Handbook (NSSH) references and refers users to NEH630.07 as the official hydrologic soil group (HSG) reference. Updating the hydrologic soil groups was originally planned and developed based on this perspective.

Listing HSGs by soil map unit component and not by soil series is a new concept for the engineers. Past engineering references contained lists of HSGs by soil series. Soil series are continually being defined and redefined, and the list of soil series names changes so frequently as to make the task of maintaining a single national list virtually impossible. Therefore, no such lists will be maintained. All such references are obsolete and their use should be discontinued.

Instructions for obtaining HSG information can be found in the introduction of this chapter.

Chapter 7 Hydrologic Soil Groups

Contents:

Chapter 7 Hydrologic Soil Groups

630.0700 Introduction

This chapter defines four hydrologic soil groups, or HSGs, that, along with land use, management practices, and hydrologic conditions, determine a soil's associated runoff curve number (NEH630.09). Runoff curve numbers are used to estimate direct runoff from rainfall (NEH630.10).

A map unit is a collection of areas defined and named the same in terms of their soil components or miscellaneous areas or both (NSSH 627.03). Soil scientists assign map unit components to hydrologic soil groups. Map unit components assigned to a specific hydrologic soil group have similar physical and runoff characteristics. Soils in the United States, its territories, and Puerto Rico have been assigned to hydrologic soil groups. The assigned groups can be found by consulting the Natural Resources Conservation Service's (NRCS) Field Office Technical Guide; published soil survey data bases; the NRCS Soil Data Mart Web site (*http://soildatamart.nrcs.usda.gov/*); and/or the Web Soil Survey Web site (*http://websoilsurvey.nrcs.usda.gov/*).

The NRCS State soil scientist should be contacted if a soil survey does not exist for a given area or where the soils within a watershed have not been assigned to hydrologic groups.

630.0701 Hydrologic soil groups

Soils were originally assigned to hydrologic soil groups based on measured rainfall, runoff, and infiltrometer data (Musgrave 1955). Since the initial work was done to establish these groupings, assignment of soils to hydrologic soil groups has been based on the judgment of soil scientists. Assignments are made based on comparison of the characteristics of unclassified soil profiles with profiles of soils already placed into hydrologic soil groups. Most of the groupings are based on the premise that soils found within a climatic region that are similar in depth to a restrictive layer or water table, transmission rate of water, texture, structure, and degree of swelling when saturated, will have similar runoff responses. The classes are based on the following factors:

- intake and transmission of water under the conditions of maximum yearly wetness (thoroughly wet)
- soil not frozen
- bare soil surface
- maximum swelling of expansive clays

The slope of the soil surface is not considered when assigning hydrologic soil groups.

In its simplest form, hydrologic soil group is determined by the water transmitting soil layer with the lowest saturated hydraulic conductivity and depth to any layer that is more or less water impermeable (such as a fragipan or duripan) or depth to a water table (if present). The least transmissive layer can be any soil horizon that transmits water at a slower rate relative to those horizons above or below it. For example, a layer having a saturated hydraulic conductivity of 9.0 micrometers per second (1.3 inches per hour) is the least transmissive layer in a soil if the layers above and below it have a saturated hydraulic conductivity of 23 micrometers per second (3.3 inches per hour).

Water impermeable soil layers are among those types of layers recorded in the component restriction table of the National Soil Information System (NASIS) database. The saturated hydraulic conductivity of an impermeable or nearly impermeable layer may range from essentially 0 micrometers per second (0 inches per hour) to 0.9 micrometers per second (0.1 inches per hour). For simplicity, either case is considered impermeable for hydrologic soil group purposes. In some cases, saturated hydraulic conductivity (a quantitatively measured characteristic) data are not always readily available or obtainable. In these situations, other soil properties such as texture, compaction (bulk density), strength of soil structure, clay mineralogy, and organic matter are used to estimate water movement. Table 7–1 relates saturated hydraulic conductivity to hydrologic soil group.

The four hydrologic soil groups (HSGs) are described as:

Group A—Soils in this group have low runoff potential when thoroughly wet. Water is transmitted freely through the soil. Group A soils typically have less than 10 percent clay and more than 90 percent sand or gravel and have gravel or sand textures. Some soils having loamy sand, sandy loam, loam or silt loam textures may be placed in this group if they are well aggregated, of low bulk density, or contain greater than 35 percent rock fragments.

The limits on the diagnostic physical characteristics of group A are as follows. The saturated hydraulic conductivity of all soil layers exceeds 40.0 micrometers per second (5.67 inches per hour). The depth to any water impermeable layer is greater than 50 centimeters [20 inches]. The depth to the water table is greater than 60 centimeters [24 inches]. Soils that are deeper than 100 centimeters [40 inches] to a water impermeable layer and a water table are in group A if the saturated hydraulic conductivity of all soil layers within 100 centimeters [40 inches] of the surface exceeds 10 micrometers per second (1.42 inches per hour).

Group B—Soils in this group have moderately low runoff potential when thoroughly wet. Water transmission through the soil is unimpeded. Group B soils typically have between 10 percent and 20 percent clay and 50 percent to 90 percent sand and have loamy sand or sandy loam textures. Some soils having loam, silt loam, silt, or sandy clay loam textures may be placed in this group if they are well aggregated, of low bulk density, or contain greater than 35 percent rock fragments.

The limits on the diagnostic physical characteristics of group B are as follows. The saturated hydraulic conductivity in the least transmissive layer between the surface and 50 centimeters [20 inches] ranges from 10.0 micrometers per second (1.42 inches per hour) to 40.0 micrometers per second (5.67 inches per hour). The depth to any water impermeable layer is greater than 50 centimeters [20 inches]. The depth to the water table is greater than 60 centimeters [24 inches]. Soils that are deeper than 100 centimeters [40 inches] to a water impermeable layer and a water table are in group B if the saturated hydraulic conductivity of all soil layers within 100 centimeters [40 inches] of the surface exceeds 4.0 micrometers per second (0.57 inches per hour) but is less than 10.0 micrometers per second (1.42 inches per hour).

Group C—Soils in this group have moderately high runoff potential when thoroughly wet. Water transmission through the soil is somewhat restricted. Group C soils typically have between 20 percent and 40 percent clay and less than 50 percent sand and have loam, silt loam, sandy clay loam, clay loam, and silty clay loam textures. Some soils having clay, silty clay, or sandy clay textures may be placed in this group if they are well aggregated, of low bulk density, or contain greater than 35 percent rock fragments.

The limits on the diagnostic physical characteristics of group C are as follows. The saturated hydraulic conductivity in the least transmissive layer between the surface and 50 centimeters [20 inches] is between 1.0 micrometers per second (0.14 inches per hour) and 10.0 micrometers per second (1.42 inches per hour). The depth to any water impermeable layer is greater than 50 centimeters [20 inches]. The depth to the water table is greater than 60 centimeters [24 inches]. Soils that are deeper than 100 centimeters [40 inches] to a restriction and a water table are in group C if the saturated hydraulic conductivity of all soil layers within 100 centimeters [40 inches] of the surface exceeds 0.40 micrometers per second (0.06 inches per hour) but is less than 4.0 micrometers per second (0.57 inches per hour).

Group D—Soils in this group have high runoff potential when thoroughly wet. Water movement through the soil is restricted or very restricted. Group D soils typically have greater than 40 percent clay, less than 50 percent sand, and have clayey textures. In some areas, they also have high shrink-swell potential. All soils with a depth to a water impermeable layer less than 50 centimeters [20 inches] and all soils with a water table within 60 centimeters [24 inches] of the surface are in this group, although some may have a dual classification, as described in the next section, if they can be adequately drained.

The limits on the physical diagnostic characteristics of group D are as follows. For soils with a water impermeable layer at a depth between 50 centimeters and 100 centimeters [20 and 40 inches], the saturated hydraulic conductivity in the least transmissive soil layer is less than or equal to 1.0 micrometers per second (0.14 inches per hour). For soils that are deeper than 100 centimeters [40 inches] to a restriction or water table, the saturated hydraulic conductivity of all soil layers within 100 centimeters [40 inches] of the surface is less than or equal to 0.40 micrometers per second (0.06 inches per hour).

Dual hydrologic soil groups—Certain wet soils are placed in group D based solely on the presence of a water table within 60 centimeters [24 inches] of the surface even though the saturated hydraulic conductivity may be favorable for water transmission. If these soils can be adequately drained, then they are assigned to dual hydrologic soil groups (A/D, B/D, and C/D) based on their saturated hydraulic conductivity and the water table depth when drained. The first letter applies to the drained condition and the second to the undrained condition. For the purpose of hydrologic soil group, adequately drained means that the seasonal high water table is kept at least 60 centimeters [24 inches] below the surface in a soil where it would be higher in a natural state.

Matrix of hydrologic soil group assignment criteria—The decision matrix in table 7–1 can be used to determine a soil's hydrologic soil group. If saturated hydraulic conductivity data are available and deemed to be reliable, then these data, along with water table depth information, should be used to place the soil into the appropriate hydrologic soil group. If these data are not available, the hydrologic soil group is determined by observing the properties of the soil in the field. Factors such as texture, compaction (bulk density), strength of soil structure, clay mineralogy, and organic matter are considered in estimating the hydraulic conductivity of each layer in the soil profile. The depth and hydraulic conductivity of any water impermeable layer and the depth to any high water table are used to determine correct hydrologic soil group for the soil. The property that is most limiting to water movement generally determines the soil's hydrologic group. In anomalous situations, when adjustments to hydrologic soil group become necessary, they shall be made by the NRCS State soil scientist in consultation with the State conservation engineer.

Table 7–1 Criteria for assignment of hydrologic soil group (HSG)

Depth to water impermeable layer [1/]	Depth to high water table [2/]	K_{sat} of least transmissive layer in depth range	K_{sat} depth range	HSG [3/]
<50 cm [<20 in]	—	—	—	D
50 to 100 cm [20 to 40 in]	<60 cm [<24 in]	>40.0 µm/s (>5.67 in/h)	0 to 60 cm [0 to 24 in]	A/D
		>10.0 to ≤40.0 µm/s (>1.42 to ≤5.67 in/h)	0 to 60 cm [0 to 24 in]	B/D
		>1.0 to ≤10.0 µm/s (>0.14 to ≤1.42 in/h)	0 to 60 cm [0 to 24 in]	C/D
		≤1.0 µm/s (≤0.14 in/h)	0 to 60 cm [0 to 24 in]	D
	≥60 cm [≥24 in]	>40.0 µm/s (>5.67 in/h)	0 to 50 cm [0 to 20 in]	A
		>10.0 to ≤40.0 µm/s (>1.42 to ≤5.67 in/h)	0 to 50 cm [0 to 20 in]	B
		>1.0 to ≤10.0 µm/s (>0.14 to ≤1.42 in/h)	0 to 50 cm [0 to 20 in]	C
		≤1.0 µm/s (≤0.14 in/h)	0 to 50 cm [0 to 20 in]	D
>100 cm [>40 in]	<60 cm [<24 in]	>10.0 µm/s (>1.42 in/h)	0 to 100 cm [0 to 40 in]	A/D
		>4.0 to ≤10.0 µm/s (>0.57 to ≤1.42 in/h)	0 to 100 cm [0 to 40 in]	B/D
		>0.40 to ≤4.0 µm/s (>0.06 to ≤0.57 in/h)	0 to 100 cm [0 to 40 in]	C/D
		≤0.40 µm/s (≤0.06 in/h)	0 to 100 cm [0 to 40 in]	D
	60 to 100 cm [24 to 40 in]	>40.0 µm/s (>5.67 in/h)	0 to 50 cm [0 to 20 in]	A
		>10.0 to ≤40.0 µm/s (>1.42 to ≤5.67 in/h)	0 to 50 cm [0 to 20 in]	B
		>1.0 to ≤10.0 µm/s (>0.14 to ≤1.42 in/h)	0 to 50 cm [0 to 20 in]	C
		≤1.0 µm/s (≤0.14 in/h)	0 to 50 cm [0 to 20 in]	D
	>100 cm [>40 in]	>10.0 µm/s (>1.42 in/h)	0 to 100 cm [0 to 40 in]	A
		>4.0 to ≤ 10.0 µm/s (>0.57 to ≤1.42 in/h)	0 to 100 cm [0 to 40 in]	B
		>0.40 to ≤4.0 µm/s (>0.06 to ≤0.57 in/h)	0 to 100 cm [0 to 40 in]	C
		≤0.40 µm/s (≤0.06 in/h)	0 to 100 cm [0 to 40 in]	D

1/ An impermeable layer has a K_{sat} less than 0.01 µm/s [0.0014 in/h] or a component restriction of fragipan; duripan; petrocalcic; orstein; petrogypsic; cemented horizon; densic material; placic; bedrock, paralithic; bedrock, lithic; bedrock, densic; or permafrost.

2/ High water table during any month during the year.

3/ Dual HSG classes are applied only for wet soils (water table less than 60 cm [24 in]). If these soils can be drained, a less restrictive HSG can be assigned, depending on the K_{sat}.

630.0702 Disturbed soils

As a result of construction and other disturbances, the soil profile can be altered from its natural state and the listed group assignments generally no longer apply, nor can any supposition based on the natural soil be made that will accurately describe the hydrologic properties of the disturbed soil. In these circumstances, an onsite investigation should be made to determine the hydrologic soil group. A general set of guidelines for estimating saturated hydraulic conductivity from field observable characteristics is presented in the Soil Survey Manual (Soil Survey Staff 1993).

630.0703 References

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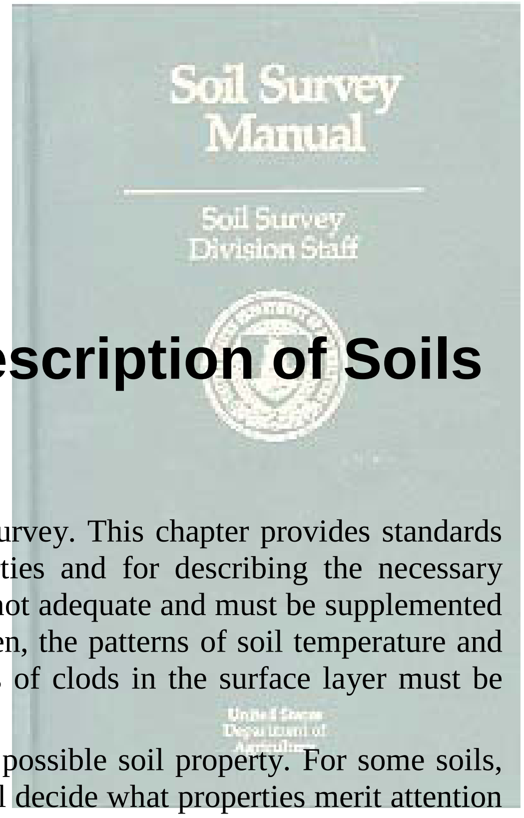
CHAPTER 3

Examination and Description of Soils



A description of the soils is essential in any soil survey. This chapter provides standards and guidelines for describing most soil properties and for describing the necessary related facts. For some soils, standard terms are not adequate and must be supplemented by a narrative. The length of time that cracks remain open, the patterns of soil temperature and moisture, and the variations in size, shape, and hardness of clods in the surface layer must be observed over time and summarized.

This chapter does not include a discussion of every possible soil property. For some soils, other properties need to be described. Good judgment will decide what properties merit attention in detail for any given pedon (sampling unit). Observations must not be limited by preconceived ideas about what is important.

Although the format of the description and the order in which individual properties are described are less important than the content of the description, a standard format has distinct advantages. The reader can find information more rapidly, and the writer is less likely to omit important features. Furthermore, a standard format makes it easier to code data for automatic processing. If forms are used, they must include space for all possible information. Formats for recording and retrieving information about pedons will be discussed in more detail in chapter 5.

Each investigation of the internal properties of a soil is made on a soil body of some dimensions. The body may be larger than a pedon or represent a portion of a pedon. During field operations, many soils are investigated by examining the soil material removed by a sampling tube or an auger. For rapid investigations of thin soils, a small pit can be dug and a section of soil removed with a spade. All of these are samples of pedons. Knowledge of the internal properties of a soil is derived mainly from studies of such samples. They can be studied more rapidly than entire pedons; consequently, a much larger number can be studied in many more places. For many soils, the information obtained from such a small sample describes the pedon from which it is taken with few omissions. For other soils, however, important properties of a pedon are not observable in the smaller sample, and detailed studies of entire pedons may be needed. Complete study of an entire pedon requires the exposure of a vertical section and the removal of horizontal sections layer by layer. Horizons are studied in both horizontal and vertical dimensions.

Some General Terms Used in Describing Soils

Several of the general terms for internal elements of the soil are described here; other more specific terms are described or defined in the following sections.

A soil profile is exposed by a vertical cut through the soil. It is commonly conceived as a plane at right angles to the surface. In practice, a description of a soil profile includes soil

Class 4. This class consists of soils that have lost all of the original A and/or E horizons or the uppermost 20 cm if the original A and/or E horizons were less than 20 cm thick. In addition, Class 4 includes some or all of the deeper horizons throughout most of the area. The original soil can be identified only in small areas. Some areas may be smooth, but most have an intricate pattern of gullies. Figure 3-9 is an example of class 4 erosion.

FIGURE 3-9

Class 4 erosion intermingled with class 3 erosion. The areas in the middle and left have lost almost all diagnostic horizons. The areas in the foreground and far background have class 3 erosion.

Soil Water

This section discusses "the water regime"—schemes for the description of the state of the soil water at a particular time and for the change in soil water state over time. Soil water state is evaluated from water suction, quantity of water, whether the soil water is liquid or frozen, and the occurrence of free water within the soil and on the land surface. Complexity and detail of water regime statements may range widely.

Inundation Classes

Free water may occur above the soil. Inundation is the condition that the soil area is covered by liquid free water. Flooding is temporary inundation by flowing water. If the water is standing, as in a closed depression, the term ponding is used.

Internal Classes

Definitions.—Table 3-2 contains water state classes for the description of individual layers or horizons. Only matrix suction is considered in definition of the classes.[4] Osmotic potential is not considered. For water contents of medium and fine-textured soil materials at suctions less than about 200 kPa, the reference laboratory water retention is for the natural soil fabric. Class limits are expressed both in terms of suction and water content. In order to make field and field office evaluation more practicable, water content pertains to gravimetric quantities and not to volumetric. The classes are applicable to organic as well as to mineral soil material. The frozen condition is indicated separately by the symbol "f." The symbol indicates the presence of ice; some of the water may not be frozen. If the soil is frozen, the water content or suction pertains to what it would be if not frozen.

Table 3-2. Water state classes

Class	Criteria[a]
Dry (D)	>1500 kPa suction
Very Dry (DV)	<(0.35 x 1500 kPa retention)
Moderately Dry (DM)	0.35 to 0.8 x 1500 kPa retention
Slightly Dry (DS)	0.8 to 1.0 x 1500 kPa retention
Moist (M)	<1500 kPa to >1 or 1/2 kPa[b]
Slightly Moist (MS)	1500 kPa suction to MWR[c]
Moderately Moist (MM)	MWR to UWR[c]
Very Moist (MV)	UWR to 1 or 1/2 kPa[b] suction
Wet (W)	<1 kPa or <1/2 kPa[b]
Nonsatiated (WN)	No free water
Satiated (WA)	Free water present

[a] Criteria use both suction and gravimetric water contents as defined by suction.

[b] 1/2 kPa only if coarse soil material (see text).

[c] UWR is the abbreviation for upper water retention, which is the laboratory water retention at 5 kPa for coarse soil material and 10 kPa for other (see text). MWR is the midpoint water retention. It is halfway between the upper water retention and the retention at 1500 kPa.

[4] The primary unit for suction is the pascal (symbol, Pa). The kilopascal (symbol kPa) is commonly employed. A kilopascal is 1000x a pascal. One bar is 100 kilopascals.

Three classes and eight subclasses are defined. Classes and subclasses may be combined as desired. Symbols for the combinations currently defined are in table 3-2. Specificity desired and characteristics of the water desorption curve would determine whether classes or subclasses would be used. Coarse soil material has little water below the 1500 kPa retention, and so subdivisions of dry generally would be less useful.

Dry is separated from *moist* at 1500 kPa suction. *Wet* is separated from moist at the condition where water films are readily apparent. The water suction at the moist-wet boundary is assumed to be about 1/2 kPa for coarse soil materials and 1 kPa for other materials. The formal definition of coarse soil material is given later.

Three subclasses of dry are defined—*very dry*, *moderately dry*, and *slightly dry*. Very dry cannot be readily distinguished from air dry in the field. The water content extends from ovendry to 0.35 times the water retention at 1500 kPa. The upper limit is roughly 150 percent of the air dry water content. The limit between moderately dry and slightly dry is a water content 0.8 times the retention at 1500 kPa.

The moist class is subdivided into *slightly moist, moderately moist,* and *very moist*. Depending on the kind of soil material, laboratory retention at 5 or 10 kPa suction (method 4B, Soil Survey Laboratory Staff, 1992) determines the *upper water retention*. A suction of 5 kPa is employed for coarse soil material. Otherwise, 10 kPa is used.

> To be considered coarse, the soil material that is strongly influenced by volcanic ejecta must be nonmedial and weakly or nonvesicular. If not strongly influenced by volcanic ejecta, it must meet the sandy or sandy-skeletal family particle size criteria and also be coarser than loamy fine sand, have <2 percent organic carbon, and have <5 percent water at 1500 kPa suction. Furthermore, the computed total porosity of the <2 mm fabric must exceed 35 percent.[5]

Very moist has an upper limit at the moist-wet boundary and a lower limit at the upper water retention. Relatedly, *moderately moist* has an upper limit at the upper water retention and a lower limit at the midpoint in gravimetric water content between retention at 1500 kPa and the upper water retention. This lower limit is referred to as the midpoint water retention. *Slightly moist*, in turn, extends from the midpoint water retention to the 1500 kPa retention.

The wet class has *nonsatiated* and *satiated* subclasses distinguished on the basis of absence or presence of free water. Miller and Bresler (1977) defined satiation as the condition from the first appearance of free water through saturation. The nonsatiated wet state may be applicable at

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[5] Total porosity = 100 - (100 x Db/Dp), where Db is the bulk density of the < 2mm material at or near field capacity and Dp is the particle density.

The particle density may be computed from the following:

Dp = 100/[[(1.7xOC)/Dp1] + [(1.6xFe)/Dp2] + [[100 - [(1/7xOC) + (1.6xFe)]]/Dp3]]

where OC is the organic carbon percentage and Fe is the extractable iron by method 6C2 (Soil Survey Laboratory Staff, 1992)or an equivalent method. The particle density of the organic matter (Dp1) is assumed to be 1.4 Mg/m^3, that of the minerals from which the extractable iron originates (Dp2) to be 4.2 Mg/m^3, and the material exclusive of the organic matter and the minerals contributing to the extractable Fe (Dp3) to be 2.65 Mg/m^3.

zero suction to horizons with low or very low saturated hydraulic conductivity. These horizons may not exhibit free water. Horizons may have parts that are *satiated wet* and other parts, because of low matrix saturated hydraulic conductivity and the absence of conducting macroscopic pores, that are *nonsatiated wet*. Free water develops positive pressure with depth below the top of a wet satiated zone.

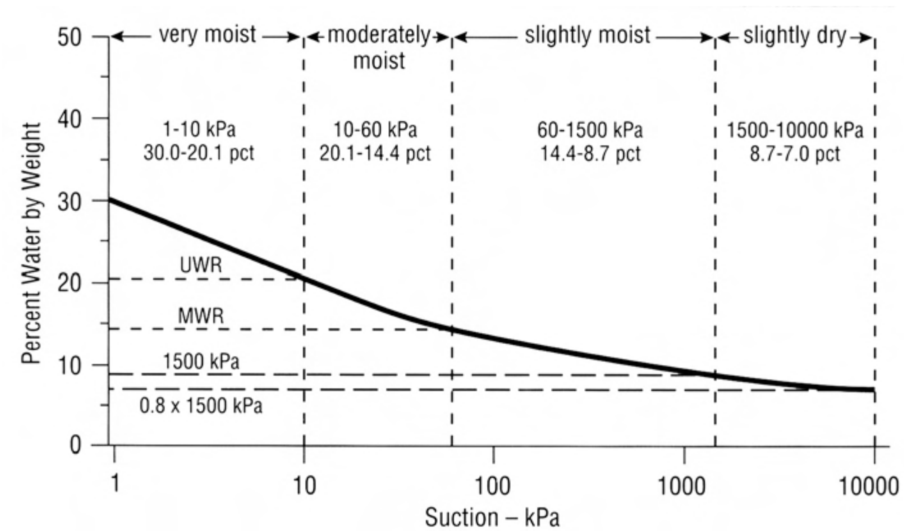
A class for saturation (that is, zero air-filled porosity) is not provided because the term suggests that all of the pore space is filled with water. This condition usually cannot be evaluated in the field. Further, if saturation is used for the concept of satiation, then a term is not available to describe known saturation. There is an implication of saturation if the soil material is satiated wet and coarse-textured or otherwise has properties indicative of high or very high saturated hydraulic conductivity throughout the mass. A satiated condition does not necessarily indicate reducing conditions. Air may be present in the water and/or the microbiological activity may be low. The presence of reducing conditions may be inferred from soil color in some instances and a test may be performed for ferrous iron in solution. The results of the test for ferrous iron should be reported separately from the water-state description.

Evaluation.—*Wet* is indicated by the occurrence of prominent water films on surfaces of sand grains and structural units that cause the soil material to glisten. If free water is absent, the term *nonsatiated wet* is used. If free water is present, the term *satiated wet* is used. The position of the upper field boundary of the satiated wet class, in a formal sense, is the top of the water in an unlined bore hole after equilibrium has been reached. Determination of the thickness of a perched zone of free water requires the installation of lined bore holes or piezometers to several depths across the zone of free water occurrence. Piezometers are tubes placed to the designated depth that are open at both ends, may have a perforated zone at the bottom, but do not permit water entry along most of their length. In the context here, information about the depth of free water and location and thickness of the free water zone would be obtained in the course of soil examination for a range of purposes and does not necessarily require installation of bore holes.

Ideally, evaluation within the moist and dry classes should be based on field instrumentation. Usually, such instrumentation is not available and approximations must be made. Gravimetric water content measurements may be used. To make the conversion from measured water content to suction it is necessary to have information on the gravimetric water retention at different suctions. The water retention at 1500 kPa may be estimated from the field clay percentage evaluation if dispersion of clay is relatively complete for the soils of concern. Commonly, the 1500 kPa retention is roughly 0.4 times the clay percentage. This relationship can be refined considerably as the soil material composition and organization is increasingly specified. Another rule of thumb is that the water content at air-dryness is about 10 percent of the clay percentage, assuming complete dispersion. Model-based curves that relate gravimetric water content and suction are available for many soils (Baumer, 1986). These curves may be used to determine upper water retention and the midpoint water retention, and to place the soil material in a water state class based on gravimetric water contents. Further such curves would be the basis in many instances for estimation of the water retention at 10 kPa from measurements at 33 kPa. Figure 3-10 shows a model-based curve for a medium-textured horizon and the relationship of water-state class limits to water contents determined from the desorption curve. The figure includes the results of a set of tests designed to provide local criteria for field and field office evaluation of water state. These will be discussed subsequently.

Commonly, gravimetric water content information is not available. Visual and tactile observations must suffice for the placement. Separation between moist and wet and the distinction between the two subclasses of wet may be made visually, based on water-film expression and presence of free water. Similarly, the separation between very dry and

FIGURE 3-10



Model-based curve for a medium-textured horizon and the relationships of water state class limits to water contents determined from the desorption curve.

moderately dry can be made by visual or tactile comparison of the soil material at the field water content and after air drying. The change on air drying should be quite small, if the soil material initially is in the very dry class.

Criteria are more difficult to formulate for soil material that is between the moist/wet and the moderately dry/very dry separations. Four tests follow that may be useful for mineral soils. The three tests that involve tactile examination are performed on soil material that has been manipulated and mixed. This manipulation and mixing may change the tactile qualities from that of weakly altered soil material. The change may be particularly large for dense soil. In the field, this limitation should be kept in mind.

Color value test. The crushed color value of the soil for an unspecified water state is compared to the color value at air dryness and while moderately moist or very moist. This test probably has usefulness only if the full range of color value from air dry to moderately moist exceeds one unit of color value. The change in color value and its interpretation depends on the water desorption characteristics of the soil material. For example, as the water retention at 1500 kPa increases, the difference between the minimum color value in the dry state and the very moist color value tends to decrease.

Ball test. A quantity of soil is squeezed firmly in the palm of the hand to form a ball about 3 to 4 cm in diameter. This is done in about five squeezes. The sphere should be near the maximum density that can be obtained by squeezing. Preparation of the ball will differ among people. The important point is that the procedure is consistent for an individual.

In one approach, the ball is dropped from progressively increasing heights onto a nonresilient surface. The height in centimeters at which rupture occurs is recorded. Usually heights above 100 cm are not measured. Additionally, the manner of rupture is recorded. If the ball flattens and does not rupture, the term "deforms" is used. If the ball breaks into about five or less units, the term "pieces" is used. Finally, if the number of units exceeds about five, the term "crumbles" is used.

Alternatively, penetration resistance may be used. The penetrometer is inserted in the ball in the same fashion as would be done for soil in place. This alternative is only applicable for medium and fine- textured soil materials at higher water contents because these soil materials are relatively plastic and not subject to cracking.

Rod test. The soil material is rolled between thumb and first finger or on a surface to form a rod 3 mm in diameter or less. This rod must remain intact while being held vertically from an end for recognition as a rod. Minimum length required is 2 cm. If the maximum length that can be formed is 2 to 5 cm, the rod is weak. If the maximum length equals or exceeds 5 cm, the rod is strong.

The rod test has close similarities to the plastic limit test (ASTM, 1984). Plastic limit values exceed the 1500 kPa retention at moderate clay contents and approach but are not commonly lower than the 1500 kPa retention at high clay contents. If a strong rod can be formed, the water content usually exceeds the 1500 kPa retention. The same is probably true for a weak rod. An adjustment is necessary if material of 2 to 0.5 mm is present because the plastic limit is measured on material that passes a number 40 sieve (0.43 mm in diameter).

Ribbon test. The soil material is smeared out between thumb and first finger to form a flattened body about 2 mm of thickness. The minimum length of a coherent unit required for recognition of a ribbon is 2 cm. If the maximum length is 2 to 4 cm, the ribbon is weak. If the maximum length equals or exceeds 4 cm, the ribbon is strong.

To establish criteria based on the foregoing tests it is highly desirable to apply the tests first to soil materials that are known to be at water-state class limits. The approach would parallel that used to maintain quality control of field texture evaluation. The first step to obtain such samples is to establish gravimetric water contents for the class limits (table 3-2). Soil material is prepared at these water contents. A known weight of soil material at a measured, initially higher, water content than the desired final content is placed in a commercial, nylon oven-cooking bag. These bags pass from 1 to 10 grams per hour of water at room temperature, depending on the size, the air temperature, humidity, and movement. Water loss from the bag is continued until the predetermined weight (hence, desired water content) is reached. If long-term storage is desired, the soil is next transferred to glass canning jars. The soil material either may be dried from an initially higher field water content after passing through a number 4 sieve (4.8 mm) or may be air-dried, ground, wetted to above the desired final water content, and then dried. It is preferable to pass the soil through a number 4 sieve (4.8 mm) rather than a number 10 (2 mm). The natural organization is retained to a greater extent. As a result, the calibration sample feels more like it would under field conditions. For the higher suctions, consideration should be given to storage of the soil material for a day or two after the water content reduction to improve equilibration.

General relationships of the tests to water state, with the exception of the relationship of the rod test to 1500 kPa retention, have not been formulated and are probably not feasible. The tests may be applied to groupings of soils based on composition, and then locally applicable field criteria can be formulated. Table 3-3 illustrates much of the range in test results that may be expected within a soil survey in central Nebraska.

Table 3-3. Water state calibration tests on three soil materials differing in texture from central Nebraska.

Soil [a/]	Sand	Silt	Clay	Organic Matter	MWR [b/]	1500 kPa- [b/]	Water Content	Height	Ball Penetration Failure	Resistance	Rod	Ribbon	Color Value
	Pct	Pct	Pct	Pct	Pct	Pct	Pct	cm		MPa	cm	cm	
Hastings	5	57	38	1.4	26.2	18.8	>UWR						3
							MWR	>100	Deform	1.1	7	7	3
							1500 kPa	>100	Deform	Crack	1	3	4
							0.8x1500 kPa	50	Pieces	Crack	No	1/2	4
							Air Dry						5
Lockton	53	33	14	1.6	12.9	7.6	>UWR						2.5
							MWR	60	Pieces		No	3	3
							1500 kPa	30	Pieces		No	2	3.5
							0.8 x 1500 kPa	10	Crumbles		No	No	3.5
							Air Dry						3.5
Valentine	82	13	5	1.1	9.4	3.7	>UWR						3
							MWR	< 2	Pieces		No	No	3.5
							1500 kPa	< 5	Crumbles		No	No	4
							0.8 x 1500 kPa						
							Air Dry						4.5

a/ Hastings is a fine, montmorillonitic, mesic Udic Argiustoll; Lockton is a fine-loamy over sandy or sandy-skeletal, mixed, mesic Cumulic Haplustoll; and Valentine is a mixed, mesic Typic Ustipsamment. The Hastings sample is a silty clay loam; Lockton is a sandy loam; and Valentine is a loamy fine sand. All are from the upper subsoil. Montmorillonite is the dominant clay mineral. Soil materials with certain other clay mineralogies feel drier at 1500 kPa than do these samples.

b/ Both gravimetric. MWR: (10 kPa plus 1500 kPa retention)/2

Natural Drainage Classes

Natural drainage class refers to the frequency and duration of wet periods under conditions similar to those under which the soil developed. Alteration of the water regime by man, either through drainage or irrigation, is not a consideration unless the alterations have significantly changed the morphology of the soil. The classes follow:

Excessively drained. Water is removed very rapidly. The occurrence of internal free water commonly is very rare or very deep. The soils are commonly coarse-textured and have *very high hydraulic conductivity* or are very shallow.

Somewhat excessively drained. Water is removed from the soil rapidly. Internal free water occurrence commonly is very rare or very deep. The soils are commonly coarse-textured and have *high saturated hydraulic conductivity* or are very shallow.

Well drained. Water is removed from the soil readily but not rapidly. Internal free water occurrence commonly is deep or very deep; annual duration is not specified. Water is available to plants throughout most of the growing season in humid regions. Wetness does not inhibit growth of roots for significant periods during most growing seasons. The soils are mainly free of the deep to redoximorphic features that are related to wetness.

Moderately well drained. Water is removed from the soil somewhat slowly during some periods of the year. Internal free water occurrence commonly is moderately deep and transitory through permanent. The soils are wet for only a short time within the rooting depth during the growing season, but long enough that most mesophytic crops are affected. They commonly have a *moderately low* or *lower saturated hydraulic conductivity* in a layer within the upper 1 m, periodically receive high rainfall, or both.

Somewhat poorly drained. Water is removed slowly so that the soil is wet at a shallow depth for significant periods during the growing season. The occurrence of internal free water commonly is shallow to *moderately deep* and transitory to permanent. Wetness markedly restricts the growth of mesophytic crops, unless artificial drainage is provided. The soils commonly have one or more of the following characteristics: low or very *low saturated hydraulic conductivity*, a high water table, additional water from seepage, or nearly continuous rainfall.

Poorly drained. Water is removed so slowly that the soil is wet at shallow depths periodically during the growing season or remains wet for long periods. The occurrence of internal free water is shallow or very shallow and common or persistent. Free water is commonly at or near the surface long enough during the growing season so that most mesophytic crops cannot be grown, unless the soil is artificially drained. The soil, however, is not continuously wet directly below plow-depth. Free water at shallow depth is usually present. This water table is commonly the result of *low* or *very low saturated hydraulic conductivity* of nearly continuous rainfall, or of a combination of these.

Very poorly drained. Water is removed from the soil so slowly that free water remains at or very near the ground surface during much of the growing season. The occurrence of internal free water is very shallow and persistent or permanent. Unless the soil is artificially drained, most mesophytic crops cannot be grown. The soils are commonly level or depressed and frequently ponded. If rainfall is high or nearly continuous, slope gradients may be greater.

Inundation Occurrence

Table 3-4 contains classes for frequency and for duration of inundation. A record of the month(s) during which the inundation occurs may be useful. Maximum depth of the inundation, as well as the flow velocity, may be helpful.

Table 3-4. Frequency and duration of inundation classes

Class	Criteria
Frequency	
None (N))	No reasonable possibility
Rare (R)	1 to 5 times in 100 years
Occasional (O)	5 to 50 times in 100 years
Frequent (F)	> 50 times in 100 years
Common (C)	Occasional and frequent can be grouped for certain purposes and called common
Duration	
Extremely Brief (BE)	< 4 hours (flooding only)
Very Brief (BV)	4 - 48 hours
Brief (B)	2 - 7 days
Long (L)	7 days to 1 month
Very Long (LV)	> 1 month

Internal Free Water Occurrence

Table 3-5 contains classes for the description of free water regime in soils. The term free water occurrence is used instead of satiated wet in order to facilitate discussion of interpretations. Classes are provided for internal free water occurrence that describe thickness if perched, depth to the upper boundary, and the aggregate time present in the calendar year. The free water need be present only in some parts of the horizon or layer to be recognized. If not designated as perched, it is assumed that the zone of free water occurs in all horizons or layers from its upper boundary to below 2 meters or to the depth of observation. Furthermore, artesian effects may be noted.

Table 3-5. Internal free water occurrence classes

Classes	Criteria
Thickness if perched	
Extremely Thin (TE)	<10 cm
Very Thin (TV)	10 to 30 cm
Thin (T)	30 cm to 1 m
Thick (TK)	>1 m
Depth	
Very Shallow (SV)	<25 cm
Shallow (S)	25 cm to 50 cm
Moderately Deep (DM)	50 cm to 1 m
Deep (D)	1.0 to 1.5 m
Very Deep (DV)	>1.5 m
Cumulative Annual Pattern	
Absent (A)	Not observed
Very Transitory (TV)	Present <1 month
Transitory (T)	Present 1 to 3 months
Common (C)	Present 3 to 6 months
Persistent (PS)	Present 6 to 12 months
Permanent (PM)	Present Continuously

Water-State Annual Pattern

The water-state annual pattern is a description of field soil water over the year as applied to horizons, layers, or to standard depth zones. Using the classes of internal water states and of inundation, table 3-6 contains examples. Usually the use of the soil is indicated and the time interval is at least monthly. More general records may be constructed based on less specific soil uses and on soil concepts at a higher categorical level. Records may be constructed for classes of relative precipitation: wet—the wettest 2 years in 10; dry—the driest 2 years in 10; and average—the conditions 6 years in 10. Unless otherwise indicated, the class placement for relative precipitation would be based on the more critical part of the growing season for the vegetation specified in the use. The frequency and duration that the soil is inundated each month may be given.

Table 3-6. Illustrative water state annual pattern. (Symbols are defined in table 3-2.)

Depth cm	Average - 6 years in 10											
	:Jan	:Feb	:Mar	:Apr	:May	:Jun	:Jul	:Aug	:Sep	:Oct	:Nov	:Dec
	Fine, montmorillonitic, mesic Typic Argiudoll [a]											
0- 25	:MM	:MM	:MM	:MM	:MM	:MM	:MS	:DS	:DS	:MS	:MM	:MM
	:F	:F	:	:	:	:	:	:	:	:	:	:F
25- 50	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MS	:MS	:MS	:MS	:MM
	:F	:F	:F	:	:	:	:	:	:	:	:	:
50-100	:MS	:MS	:MM	:MM	:MM	:MM	:MM	:MS	:MS	:MS	:MS	:MS
100-150	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM
150-200	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM
	Fine-loamy, mixed, thermic Typic Haploxeralf [b]											
0 -30	:MM	:MM	:MS	:MS	:DS	:DS	:D1[c]	:D1	:D1	:D1	:D1	:MS
30-70	:MM	:MM	:MM	:MM	:MS	:DS	:D1	:D1	:D1	:DS	:MS	:MM
70-100	:MV	:MV	:MM	:MM	:MM	:MM	:MS	:D1	:D1	:D1	:D1	:MS
120-170	:MM	:MM	:MM	:MS	:MS	:MS	:MS	:D1	:D1	:D1	:DS	:MS

[a] Otoe County, Nebraska (Sautter, 1982). Sharpsburg silty clay loam, 2-5 percent slopes. Corn (*Zea mays*) following corn. Assume: contoured, terraced, over 20 percent residue cover. Disk twice in April. Field cultivate once. Plant May 1-15. Cultivate once or twice. Harvest November 1-15. Cattle graze after harvest. Based on a discussion with H.E. Sautter, soil scientist (retired), Syracuse, Nebraska. Monthly water states based on long-term field mapping experience and water balance computations. The Sharpsburg soil series pertains to the map unit illustrative of a consociation (appendix).

[b] San Diego Area, California (Bowman, 1973). Mean annual precipitation at Escondido is 344 mm and at Thornwaite potential evaporation is 840 mm. Study area in Fallbrook sandy loam, 5 to 9 percent slopes, eroded. The study area has slightly greater slope than the upper limit of the map unit. Vegetation is annual range, fair condition. Generalizations were made originally for the 1983 National Soil Survey Conference based on field measurements in 1966 by Nettleton et al (1968), as interpreted by R.A. Dierking, soil correlator, Portland, Oregon. At the time, moderately dry and very dry were not distinguished.

[c] D1 = DV + DM.

Table 3-6 (continued)

Driest 2 years in 10

Depth cm	:Jan	:Feb	:Mar	:Apr	:May	:Jun	:Jul	:Aug	:Sep	:Oct	:Nov	:Dec
Fine, montmorillonitic, mesic Typic Argiudoll [a]												
0- 25	:MM	:MM	:MM	:MM	:MM	:MS	:DS	:DS	:DS	:MS	:MS	:MM
	:F	:F	:	:	:	:	:	:	:	:	:	:F
25- 50	:MS	:MS	:MS	:MS	:MS	:MS	:MS	:MS	:MS	:MS	:MS	:MS
	:F	:F	:F	:	:	:	:	:	:	:	:	:
50-100	:MS	:MS	:MS	:MM	:MM	:MS	:MS	:MS	:MS	:MS	:MS	:MS
100-150	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM
150-200	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM
Fine-loamy, mixed, thermic Typic Haploxeralf [b]												
0 -30	:MS	:MM	:MS	:MS	:DS	:DS	:D1	:D1	:D1	:D1	:D1	:DS
30-70	:MM	:MM	:MM	:MM	:MS	:DS	:D1	:D1	:D1	:D1	:MS	:MS
70-100	:MS	:MM	:MM	:MM	:MM	:MM	:MS	:D1	:D1	:D1	:D1	:DS
120-170	:MS	:MM	:MS	:MS	:MS	:MS	:MS	:D1	:D1	:D1	:D1	:D1

Wettest 2 years in 10

Depth cm	:Jan	:Feb	:Mar	:Apr	:May	:Jun	:Jul	:Aug	:Sep	:Oct	:Nov	:Dec
Fine, montmorillonitic, mesic Typic Argiudoll [a]												
0- 25	:MM	:MM	:MV	:MV	:MV	:MM	:MM	:MM	:MM	:MM	:MM	:MM
	:F	:F	:	:	:	:	:	:	:	:	:	:F
25-50	:MM	:MM	:MV	:MV	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM
	:F	:F	:F	:	:	:	:	:	:	:	:	:
50-100	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM
100-150	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM
150-200	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM	:MM
Fine-loamy, mixed, thermic Typic Haploxeralf [b]												
0 -30	:MM	:MM	:MM	:MS	:DS	:DS	:D1	:D1	:D1	:DS	:MS	:MM
30-70	:MV	:MV	:MM	:MM	:MS	:DS	:D1	:D1	:D1	:DS	:MM	:MV
70-100	:MV	:MV	:MM	:MM	:MM	:MM	:MS	:D1	:D1	:D1	:MS	:MM
120-170	:MM	:MM	:MS	:MS	:MS	:MS	:MS	:D1	:D1	:D1	:DS	:MS

Water Movement

Water movement concerns rates of flow into and within the soil and the related amount of water that runs off and does not enter the soil. Saturated hydraulic conductivity, infiltration rate, and surface runoff are part of the evaluation.

Saturated Hydraulic Conductivity

Water movement in soil is controlled by two factors: 1) the resistance of the soil matrix to water flow and 2) the forces acting on each element or unit of soil water. Darcy's law, the fundamental equation describing water movement in soil, relates the flow rate to these two factors. Mathematically, the general statement of Darcy's law for vertical, saturated flow is:

$$Q/At = -K_{sat}\ dH/dz$$

where the flow rate Q/At is what soil physicists call the flux density, i.e., the quantity of water Q moving past an area A, perpendicular to the direction of flow, in a time t. The vertical saturated hydraulic conductivity K_{sat} is the reciprocal, or inverse, of the resistance of the soil matrix to water flow. The term dH/dz is the hydraulic gradient, the driving force causing water to move in soil, the net result of all forces acting on the soil water. Rate of water movement is the product of the hydraulic conductivity and the hydraulic gradient.

A distinction is made between saturated and unsaturated hydraulic conductivity. Saturated flow occurs when the soil water pressure is positive; that is, when the soil matric potential is zero (satiated wet condition). In most soils this situation takes place when about 95 percent of the total pore space is filled with water. The remaining 5 percent is filled with entrapped air. If the soil remains saturated for a long time (several months or longer) the percent of the total pore space filled with water may approach 100. Saturated hydraulic conductivity cannot be used to describe water movement under unsaturated conditions.

The vertical saturated hydraulic conductivity K_{sat} is of interest here; it is the factor relating soil water flow rate (flux density) to the hydraulic gradient and is a measure of the ease of water movement in soil. K_{sat} is the reciprocal of the resistance of soil to water movement. As the resistance increases, the hydraulic conductivity decreases. Resistance to water movement in saturated soil is primarily a function of the arrangement and size distribution of pores. Large, continuous pores have a lower resistance to flow (and thus a higher conductivity) than small or discontinuous pores. Soils with high clay content generally have lower hydraulic conductivities than sandy soils because the pore size distribution in sandy soil favors large pores even though sandy soils usually have higher bulk densities and lower total porosities (total pore space) than clayey soils. As illustrated by Poiseuille's law, the resistance to flow in a tube varies as the square of the radius. Thus, as a soil pore or channel doubles in size, its resistance to flow is reduced by a factor of 4; in other words its hydraulic conductivity increases 4-fold.

Hydraulic conductivity is a highly variable soil property. Measured values easily may vary by 10-fold or more for a particular soil series. Values measured on soil samples taken within centimeters of one another may vary by 10-fold or more. In addition, measured hydraulic conductivity values for a soil may vary dramatically with the method used for measurement. Laboratory determined values rarely agree with field measurements, the differences often being on the order of 100-fold or more. Field methods generally are more reliable than laboratory methods.

Because of the highly variable nature of soil hydraulic conductivity, a single measured value is an unreliable indicator of the hydraulic conductivity of a soil. An average of several values will give a reliable estimate which can be used to place the soil in a particular hydraulic conductivity class. Log averages (geometric means) should be used rather than arithmetic averages because hydraulic conductivity is a log normally distributed property. The antilog of the average of the logarithms of individual conductivity values is the log average, or geometric mean, and should be used to place a soil into the appropriate hydraulic conductivity class. Log averages are lower than arithmetic averages.

Hydraulic conductivity classes in this manual are defined in terms of vertical, saturated hydraulic conductivity. Table 3-7 defines the vertical, saturated hydraulic conductivity classes. The saturated hydraulic conductivity classes in this manual have a wider range of values than the classes of either the 1951 *Soil Survey Manual* or the 1971 *Engineering Guide*. The dimensions of hydraulic conductivity vary depending on whether the hydraulic gradient and flux density have mass, weight, or volume bases. Values can be converted from one basis to another with the appropriate conversion factor. Usually, the hydraulic gradient is given on a weight basis and the flux density on a volume basis and the dimensions of K_{sat} are length per time. The correct SI units thus are meters per second.[6] Micrometers per second are also acceptable SI units and are more convenient (table 3-7). Table 3-8 gives the class limits in commonly used units.

Table 3-7. Saturated hydraulic conductivity classes

Class	Ksat (µm/s)
Very High	≥ 100
High	10 - 100
Moderately High	1 - 10
Moderately Low	0.1 - 1
Low	0.01 - 0.1
Very Low	< 0.01

Hydraulic conductivity does not describe the capacity of soils in their natural setting to dispose of water internally. A soil placed in a very high class may contain free water because there are restricting layers below the soil or because the soil is in a depression where water from

[6] The Soil Science Society of America prefers that all quantities be expressed on a mass basis. This results in Ksat units of kg s m-3. Other units acceptable to their society are m3 s kg-1, the result of expressing all quantities on a volume basis, and m s -1, the result of expressing the hydraulic gradient on a weight basis and flux density on a volume basis.

surrounding areas accumulates faster than it can pass through the soil. The water may actually move very slowly despite a high K_{sat}.

Table 3-8. Saturated hydraulic conductivity class limits in equivalent units

µm/s		m/s	cm/day	in/hr	cm/hr	kg s m^{-3}	m3 s kg^{-3}
100	=	10^{-4}	864.	14.17	36.0	$1.02X10^{-2}$	$1.02X10^{-8}$
10	=	10^{-5}	86.4	1.417	3.60	$1.02X10^{-3}$	$1.02X10^{-9}$
1	=	10^{-6}	8.64	0.1417	0.360	$1.02X10^{-4}$	$1.02X10^{-10}$
0.1	=	10^{-7}	0.864	0.01417	0.0360	$1.02X10^{-5}$	$1.02X10^{-11}$
0.01	=	10^{-8}	0.0864	0.001417	0.00360	$1.02X10^{-6}$	$1.02X10^{-12}$

Guidelines for K_{sat} Class Placement

Measured values of K_{sat} are available from the literature or from researchers working on the same or similar soils. If measured values are available, their geometric means should be used for class placement.

Saturated hydraulic conductivity is a fairly easy, inexpensive, and straightforward measurement. If measured values are unavailable, a project to make measurements should be considered. Field methods are the most reliable. Standard methods for measurement of K_{sat} are described in Agronomy Monograph No. 9 (Klute and Dirksen, 1986, and Amoozegar and Warrick, 1986) and in SSIR 38 (Bouma et al., 1982).

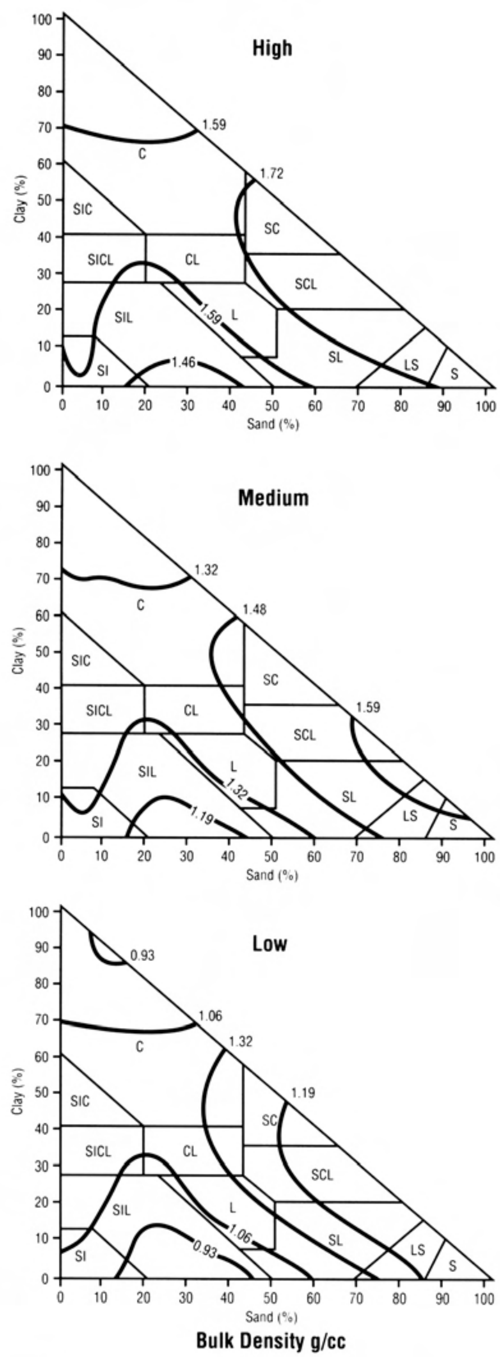
Various researchers have attempted to estimate K_{sat} based on various soil properties. These estimation methods usually use one or more of the following soil physical properties: surface area, texture, structure, bulk density, and micromorphology. The success of the individual methods varies. Often a method does fairly well in a localized area. No one method works really well for all soils. Sometimes, measurement of the predictor variables is more difficult than measurement of hydraulic conductivity. Generally, adjustments must be made for "unusual" circumstances such as high sodium concentrations, certain clay mineralogies, and the presence of coarse fragments, fragipans, and other miscellaneous features.

The method presented here is very general (Rawls and Brakensiek, 1983). It has been developed from a statistical analysis of several thousand measurements in a variety of soils. Because the method is intended for a wide application, it must be used locally with caution. The results, often, must be adjusted based on experience and local conditions.

Figure 3-11 consists of three textural triangles that can be used for K_{sat} class placement, based on soil bulk density and texture. The center triangle is for use with soils having medium or average bulk densities. The triangles above and below are for soils with high and low bulk densities, respectively.

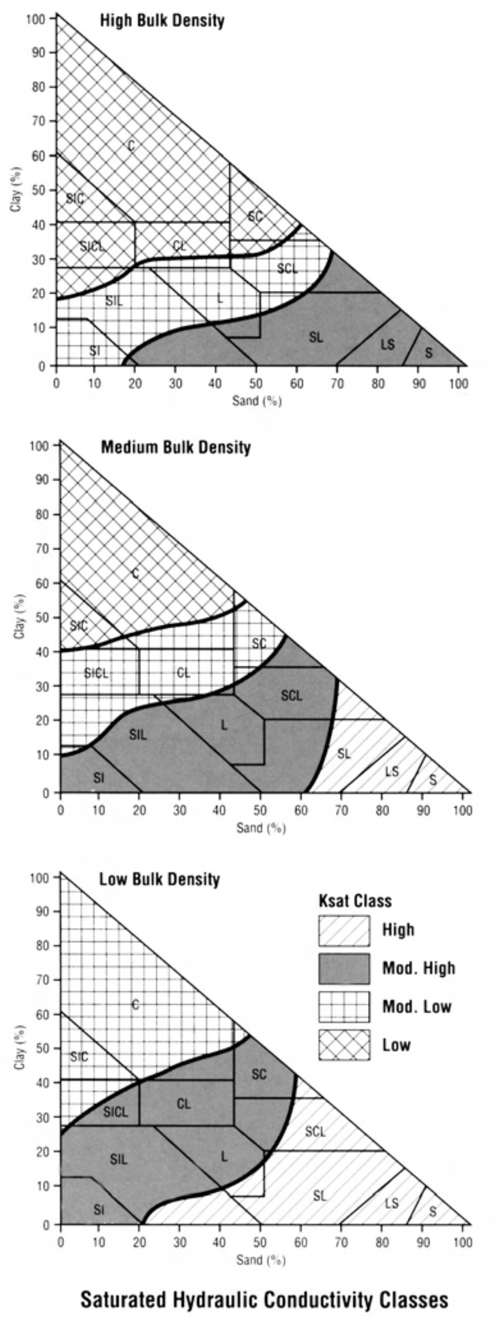
Figure 3-12 can be used to help determine which triangle in figure 3-11 to use. In each of the triangles, interpolation of the iso-bulk density lines yields a bulk density value for the particular soil texture. The triangle that provides the value closest to the measured or estimated bulk density determines the corresponding triangle in figure 3-11 that should be used.

FIGURE 3-11



Saturated hydraulic conductivity classes (Rawls and Brakensiek, 1983). A clay loam with a bulk density of 1.40 g/cc and 35 percent both sand and clay falls in the medium bulk density class.

FIGURE 3-12



Bulk density and texture relationships.

The hydraulic conductivity of a particular soil horizon is estimated by finding the triangle (fig. 3-11), based on texture and bulk density, to which the horizon belongs. The bulk density class to which the horizon belongs in Fig. 3-11 determines the triangle to be used in Fig. 3-12. The K_{sat} class can be determined immediately from the shading of the triangle. A numerical value of K_{sat} can be estimated by interpolating between the iso-K_{sat} lines; however, the values should be used with caution. The values should be used only to compare classes of soils and not as an indication of the K_{sat} of a particular site. If site values are needed, it is always best to make several measurements at the site.

The K_{sat} values given by the above procedure may need to be adjusted based on other known soil properties. Currently, there is little information available to provide adequate guidelines for adjusting the estimated K_{sat}. The soil scientist must use best judgement based on experience and the observed behavior of the particular soil.

Hydraulic conductivity can be given for the soil as a whole, for a particular horizon, or for a combination of horizons. The horizon with the lowest value determines the hydraulic conductivity classification for the whole soil. If an appreciable thickness of soil above or below the horizon with the lowest value has significantly higher conductivity, then estimates for both parts are usually given.

Infiltration

Infiltration is the process of downward water entry into the soil. The values are usually sensitive to near surface conditions as well as to the antecedent water state. Hence, they are subject to significant change with soil use and management and time.

Infiltration stages.—Three stages of infiltration may be recognized—preponded, transient ponded, and steady ponded. *Preponded infiltration* pertains to downward water entry into the soil under conditions that free water is absent on the land surface. The rate of water addition determines the rate of water entry. If rainfall intensity increases twofold, then the infiltration increases twofold. In this stage, surface-connected macropores are relatively ineffective in transporting water downward. No runoff occurs during this stage.

As water addition continues, the point may be reached where free water occurs on the ground surface. This condition is called ponding. The term in this context is less restrictive than its use in inundation. The free water may be restricted to depressions and be absent from the majority of the ground surface. Once ponding has taken place, the control over the infiltration shifts from the rate of water addition to characteristics of the soil. Surface-connected nonmatrix and subsurface-initiated cracks then become effective in transporting water downward.

Infiltration under conditions where free water is present on the ground surface is referred to as ponded infiltration. In the initial stages of *ponded infiltration*, the rate of water entry usually decreases appreciably with time because of the deeper wetting of the soil, which results in a reduced suction gradient, and the closing of cracks and other surface-connected macropores. *Transient ponded infiltration* is the stage at which the ponded infiltration decreases markedly with time. After long continued wetting under ponded conditions, the rate of infiltration becomes steady. This stage is referred to as *steady ponded infiltration*. Surface-connected cracks would be closed, if reversible. The suction gradient would be small and the driving force reduced to near that of the gravitational gradient. Assuming the absence of ice and of zones of free water within moderate depths and that surface or near surface features (crust, for example) do not control infiltration, the minimum saturated hydraulic conductivity within a depth of 1/2 to 1 meter should be a useful predictor of steady ponded infiltration rate.

Minimum Annual Steady Ponded Infiltration.—The steady ponded infiltration rate while the soil is in the wettest state that regularly occurs while not frozen is called the *minimum annual steady ponded infiltration rate*. The quantity is subject to reduction because of the presence of free water at shallow depths if this is a predictable feature of the soil. Allowance for the effect of free water differentiates the quantity from minimum saturated hydraulic conductivity for the upper meter of the soil. The minimum annual steady ponded infiltration rate has application for prediction of runoff at the wettest times of the year when the runoff potential should be the highest.

Hydrologic soil groups.—Hydrologic soil groups are employed in the computation of runoff by the Curve Number method. Minimum annual steady ponded infiltration rate for a bare ground surface determines the hydrologic soil groups. Table 3-9 contains criteria for class placement.

Table 3-9. Criteria for placement of hydrologic soil groups

Hydrologic Soil Group	Criteria[a]
A	Saturated hydraulic conductivity is *very high* or in the upper half of high and internal free water occurrence is *very deep*
B	Saturated hydraulic conductivity is in the lower half of *high* or in the upper half of *moderately high* and free water occurrence is *deep* or *very deep*.
C	Saturated hydraulic conductivity is in the lower half of *moderately high* or in the upper half of *moderately* low and internal free water occurrence is deeper than *shallow*.
D	Saturated hydraulic conductivity is below the upper half of *moderately low*, and/or internal free water occurrence is *shallow* or *very shallow* and *transitory* through *permanent*.

[a]The criteria are guidelines only. They are based on the assumption that the minimum saturated hydraulic conductivity occurs within the uppermost 0.5 m. If the minimum occurs between 0.5 and 1 m, then saturated hydraulic conductivity for the purpose of placement is increased one class. If the minimum occurs below 1 m, then the value for the soil is based on values above 1 m using the rules as previously given.

The Green-Ampt model is an example of a model used to compute infiltration rate. The model assumes that infiltrating water uniformly wets to a depth and stops abruptly at a front. This front moves downward as infiltration proceeds. The soil above the wetting front is in the satiated wet condition throughout the wetted zone.

The equation (Rawls and Brackensick, 1983) to describe infiltration is:

$$f = Ka\left(1 + \frac{MxS}{F}\right)$$

Ka is the hydraulic conductivity for satiated, but not necessarily saturated conditions; M is the porosity at a particular water state that is available to be filled with water; S is the effective suction at the wetting front; and F is the cumulative infiltration. The hydraulic conductivity at satiation is somewhat lower than the saturated value because of the presence of entrapped air. The available porosity, M, changes for surficial horizons with the bulk density and for all horizons with the water state. It is, therefore, sensitive to soil use which may affect both bulk density of surficial horizons and the antecedent water state. The value of S, the effective suction head at the wetting front, is determined largely by the texture and is a tabulated quantity. The cumulative infiltration, F, increases with time as infiltration proceeds. A consequence of the increase in the cumulative infiltration is that the infiltration rate, f, decreases with time. As the cumulative infiltration becomes large and the depth of wetting considerable, the infiltration rate should approach the value of the hydraulic conductivity for the satiated condition.

Surface Runoff

Surface runoff refers to the loss of water from an area by flow over the land surface. Surface runoff differs from subsurface flow or interflow that results when infiltrated water encounters a zone with lower perviousness than the soil above. The water accumulates above this less pervious zone and may move laterally if conditions are favorable for the occurrence of free water.

Index Surface Runoff Classes.—Historically, a set of runoff classes have been employed "as determined by the characteristics of soil slope, climate, and cover" (Soil Survey Staff, 1951). Table 3-10 contains a set of classes that parallel the sense of how the previous runoff classes were applied but with some changes in the written definitions. The current concept is referred to as index surface runoff. The concept indicates relative runoff for very specific conditions. The soil surface is assumed to be bare and surface water retention due to irregularities in the ground surface is low. Steady ponded infiltration rate is the applicable infiltration stage. Ice is assumed to be absent unless otherwise indicated. Finally, both the maximum bulk density in the upper 25 cm and the bulk density of the uppermost few centimeters are assumed within the limits specified for the mapping concept.

The concept assumes a standard storm or amount of water addition from snowmelt of 50 mm in a 24-hour period with no more than 25 mm in any single 1-hour period. Additionally, a standardized antecedent water state condition prior to the water addition is assumed: the soil is conceived to be *very moist* or *wet* to the base of the soil, to 1/2 m, or through the horizon or layer with minimum saturated hydraulic conductivity within 1 meter, whichever is the greatest depth. If the minimum saturated hydraulic conductivity of the soil occurs below 1 meter, it is disregarded and the minimum "to and including 1 m" is employed. For soils with seasonal *shallow* or *very shallow* free water, *very low* saturated hydraulic conductivity is assumed in the application of the guidelines in table 3-10.

Table 3-10. Index surface runoff classes based on slope gradient and saturated hydraulic conductivity

Slope Gradient	Saturated Hydraulic Conductivity Class [a, b]					
Pct.	***Very High***	***High***	***Mod. High***	***Mod. Low***	***Low***	***Very Low***
Concave [c]	N	N	N	N	N	N
<1	N	N	N	L	M	H
1 to 5	N	LV	L	M	H	HV
5 to 10	LV	L	M	H	HV	HV
10 to 20	LV	L	M	H	HV	HV
• 20	L	M	H	HV	HV	HV

[a] Abbreviations: Negligible-N; Very Low-LV; Low-L; Medium- M; High-H; and Very High-HV.

[b] Consult Table 3-7 for definitions. Assumes that the lowest value for the soil occurs above 1/2 m. If the lowest value occurs 1/2 to 1 m, then reduce runoff by one class (medium to slow, for example). If it occurs >1 m, then use the lowest saturated hydraulic conductivity < 1 m.

[c] Areas from which no or very little water escapes by flow over the ground surface.

Class placement (table 3-10) depends only on slope and on saturated hydraulic conductivity. Table 3-10 is based on the minimum saturated hydraulic conductivity for the soil at or above 1/2 m. If the minimum for the soil occurs between 1/2 and 1 m, the runoff should be reduced by one class (from *medium* to *low*, for example). If the lowest saturated hydraulic conductivity occurs at 1 m or deeper, the lowest value to 1 m depth should be employed rather than the lowest value for the soil.

Hydrologic models.—The set of index surface runoff classes are relative and not quantitative. Actual runoff estimates require quite different approaches. To make quantitative surface runoff estimates requires application of a hydrologic model to a watershed. Most hydrologic models involve a balancing between precipitation and infiltration rates with runoff being the difference after a correction for retention of water on the land surface and on vegetation. In the more rigorous models, the infiltration is predicted from soil physical quantities and estimates of infiltration, evapotranspiration, and deep percolation are used to predict continuously the soil water state.

An empirical model in current use is based on an analysis of a large number of runoff events for watersheds (Soil Conservation Service, 1972). A family of curves was formulated from these data to show the relationship between cumulative daily runoff and cumulative daily rainfall. Each of the family of curves is numbered&151;hence the name, Curve Number Model. The curves that describe the runoff-precipitation relationship are affected by the sum of the removals from the rainfall by infiltration, by retention on vegetation, and by storage in depressions on the land surface. If no removal of the added water has occurred, then the relationship between daily runoff and daily rainfall is a straight line at 45 degrees. As the removal increases, the departure from a 45 degree line increases. The specific curve to employ is determined by evaluation of these factors: the assumed ground surface conditions as determined by the vegetation and cultural practices, the hydrologic soil group (table 3-9), and the water storage capacity. The first factor is evaluated from land use, vegetation, and land treatment or farming practices. The second is an assessment commonly made for a soil series. The third factor is evaluated from the rainfall-evaporation balance for several days preceding the precipitation event.

Soil Temperature

Soil temperature exerts a strong influence on biological activities. It also influences the rates of chemical and physical processes within the soil. When the soil is frozen, biological activities and chemical processes essentially stop. Physical processes that are associated with ice formation are active if unfrozen zones are associated with freezing zones. Below a soil temperature of about 5 °C, growth of roots of most plants is negligible. In areas where soils have permanently frozen layers near the surface, however, even large roots of adapted plants are present immediately above the frozen layer late in the summer. Most plants grow best within a restricted range of soil and air temperature. Knowledge of soil and air temperature is essential in understanding soil-plant relationships. Temperature changes with time, as does the soil-water state. It generally differs from layer to layer at any given time.

Characteristics of Soil Temperature

Heat is both absorbed at and lost from the surface of the soil. Temperature at the surface can change in daily cycles. The soil transmits heat downward when the temperature near the surface is higher than the temperature below and heat upward when the temperature is warmer within the soil than at the surface. Soil temperatures at various depths within the soil follow cycles. The cycles deeper in the soil lag behind those near the surface. The daily cycles decrease in amplitude as depth increases and are scarcely measurable below 50 cm in most soils. Seasonal cycles are evident to much greater depths if seasonal air temperature differences are pronounced, but the temperature at a depth of 10 m is nearly constant in most soils and is about the same as the mean annual temperature of the soil above.

Soil temperature varies from layer to layer at a given site at a given time; yet, if the average annual temperatures at different depths in the same pedon are compared, they usually do not differ. Mean annual temperature is one of several useful values that describe the temperature regime of a soil.

The seasonal fluctuation of soil temperature is a characteristic of a soil. Soil temperature fluctuates little seasonally near the equator; it fluctuates widely as seasons change in the middle and high latitudes. Mean seasonal temperatures can be used to characterize soil temperature. Seasonal temperature differences decrease and the seasonal cycles lag progressively as depth increases.

For soils that freeze in winter, soil temperature is influenced by the release of heat when water changes from the liquid to the solid form. This releases about 80 calories per gram of water. The heat must be dissipated before the water in soil freezes. The rate of thaw of frozen soils is slower, because heat is required to warm the soil in order to melt the ice. In areas of