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Basic Soil and Water Resources and Irrigation Engineering/Agricultural Water Management and Related Terminology

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Background

As stated by one of the pioneer irrigation scientists Orson Winso Israelsen (1887-1968), irrigation is an age-old art that has been influencing the well-being of civilizations for thousands of years. Irrigated agriculture has been a vital part of human civilization and has been significantly contributing to food security and aiding in reducing poverty since its beginning. Today, irrigation continues to play a crucial role in meeting the food and fiber demands of a rapidly growing modern civilization as irrigated agriculture currently contributes to about 40 percent of the world's total food/fiber production on only about 20 percent of the total cultivated land. Currently, a little over 800 million acres of land is irrigated globally with surface irrigation methods being the dominant irrigation methods practiced.

A fast-growing world population, coupled with changing climate variables and increasing extreme events (both drought and floods), will likely impose substantial demand on future food and fiber production worldwide, which will, in turn, limit the availability of freshwater in producing agricultural commodities. Increasing extreme events can also increase the uncertainty in food productivity due to the uncertainty of the impact of climate change on water resources and crop response to these changes.

Estimates by the Food and Agriculture Organization of the United Nations (FAO; 2010), indicate that the world's population may reach over 9 billion by year 2050, based on the current rate of population growth. Increasing limitations in freshwater resources, coupled with population growth, have increased the competition for water between various sectors and will likely continue to increase the pressure on all disciplines to use water resources more efficiently.

However, this pressure will most likely be imposed on irrigated agriculture more than other sectors because over 70 percent of the total freshwater resources withdrawn worldwide are for irrigated agriculture. Therefore, novel ideas and quality research, as well as effective and carefully designed agricultural water management programs, need to be implemented in production fields. This will enhance crop water productivity (crop water use efficiency) to deal with these important issues and be able to keep pace with increasing food and fiber demand.

Role of Irrigation Engineering/ Agricultural Engineering Discipline

The agricultural engineering profession is in a unique position to meet the aforementioned challenges as it integrates numerous physical/natural science fundamentals to solve agriculture and natural systems/resources-related problems, including water management/irrigation engineering and crop production. In this process, an agricultural/irrigation engineer understands the complex nature of microclimate, climate, soil, water, plant physiology, and plant biophysical characteristics.

Perhaps more important, agricultural/irrigation engineers understand the interactions of these variables, agricultural machinery, as well as associated design, operation, and management principles related to agricultural structures/infrastructures. This includes irrigation systems, pumps, motor/engines, canals, etc. Control systems, data acquisition, advanced sensors and instrumentation are part of the required background to achieve this integration.

All these processes require a solid engineering background, including background in hydraulics, fluid mechanics, statics, dynamics, etc. The irrigation engineering profession is equipped with the expertise and scientific and engineering background to synthesize the knowledge and skills from several different disciplines to develop practical solutions for solving real-world problems, which is a very challenging task to accomplish.

To be effective and relevant, an agricultural engineer must be ahead of the curve related to technological developments as well as their implementation in production fields. This requires advanced understanding of soil-water-plant-atmosphere relationships in relation to developing best management practices of irrigated (and dryland) cropping systems to enhance water productivity. Accomplishing all these tasks also requires advanced understanding of engineering infrastructures, design capacity vs. water requirements, and evapotranspiration relationships to be able to accurately quantify and interpret the dynamic relationships between all these components of complex agricultural and natural systems. Thus, the irrigation engineering profession historically has been the core profession that is well-equipped to tackle many aspects of issues related to water resources, irrigation management and crop productivity.

As the irrigation engineering field itself has evolved over time, especially within the last five to six decades, basic terminologies used in irrigation and related fields have also undergone some significant changes. Similarly, common understanding or definition of irrigation and related terminology can aid in better communication between scientists, Extension personnel, producers, practitioners, and other professionals. The primary objective of this publication is to define terminology commonly used by the irrigation science community as well as by irrigation practitioners, irrigation system designers, producers, water management and regulatory agency personnel, and other professionals involved in irrigated agriculture.

Terminology

The definitions and, in some cases, their brief descriptions/explanations, of the terminology are presented in alphabetical order rather than grouping them based on topical areas. Most of the units are presented in English units, but the units of some of the variables are presented as Metric Units (The International System of Units; SI), because they are universally accepted and often used as Metric Units in theoretical and practical applications. In some cases, the sources/references used are not listed in associated specific text, but are provided in the References section. The terminologies included in this publication, in alphabetical order, are:

Bulk Density
Center Pivot Irrigation
Crop Water Use Efficiency (Crop Water Productivity)
Deep Percolation
Deficit Irrigation
Drip (Trickle) Irrigation
Effective Rainfall (Precipitation)
Evaporation
Evapotranspiration (Crop Water Use, Latent Heat Flux)
Field Capacity
Gravitational Water
Hydraulic Conductivity
Hygroscopic Water
Hysteresis (desorption and sorption)
Infiltration
Irrigation
Irrigation Application Uniformity
Irrigation Efficiency
Irrigation Requirement
Irrigation Water Use Efficiency
Leaching
Leaching Requirement
Limited Irrigation
Management Allowable Deficit or Depletion (MAD)
Microirrigation
Permeability
Permanent Wilting Point (PWP)
Readily (Easily) Available Water (RAW)
Root Zone
Runoff
Run-on
Saturation Point
Seepage
Sensitivity to Water Stress
Soil Aggregates
Soil Matric Potential
Soil Porosity
Soil Respiration
Soil Sealing (Crusting)
Soil Structure
Soil Texture

Soil Water Content
Soil Water Deficit
Subirrigation
Surface Irrigation
Surge Irrigation
Tailwater
Transpiration
Water Conveyance Efficiency
Water Holding Capacity (or Available Water Capacity)

Bulk Density: The ratio of the weight of a given volume of dry soil, including air space, to the weight of an equal volume of water. This ratio is also known as *dry bulk density* or *volume weight.* In other words, it is the ratio of the soil mass to the bulk or macroscopic volume of soil particles plus pore spaces in a soil sample. It is usually expressed as lb/ft^3 or gr/cm^3 (1 gr/cm^3 = 62.43 lb/ft^3). The mass is usually determined after drying to constant weight at 105°C (221°F), and the volume is that of the soil sample as taken in the field.

Typical or *average* bulk density values of agricultural soils vary substantially, depending on many factors, but *typical* values are: 1.45 gr/cm^3 (90.52 lb/ft^3) or greater for sandy soils; 1.40-1.45 gr/cm^3 (87.4 – 90.52 lb/ft^3) for sandy-loam soils; 1.38 gr/cm^3 (86.15 lb/ft3) or greater for loam soils; 1.25-1.35 gr/cm^3 (78.03 – 84.28 lb/ft^3) for silt-loam soils; 1.30-1.35 gr/cm^3 (81.16 – 84.28 lb/ft^3) for clay-loam soils; and 1.10-1.20 gr/cm^3 (68.67 – 74.91 lb/ft^3) for clay soils.

Bulk density varies with structural conditions of the soil and can be used as an indicator of soil structure. These bulk density values change substantially with the soil textural properties. Two soil types may belong to the same soil series (e.g., silt-loam), but can have different bulk densities. For example, one soil type may have 20 percent sand and 20 percent clay with a bulk density of 1.37 gr/cm^3 (85.53 lb/ft^3), while the other soil that consists of 20 percent sand and 10 percent clay may have a bulk density of about 1.40 gr/cm^3 (87.4 lb/ft^3); however, both soils are classified as silt-loam soils.

Bulk density will also change with the soil depth. It usually increases with depth and is also impacted substantially by soil management practices, including irrigation practices, tillage practices, within-field traffic (compaction), organic matter content, etc. Decreases in organic matter content usually result in increased bulk density in agricultural soils (Hillel, 1998).

Center Pivot Irrigation: A method of irrigation in which the system/machine rotates around a pivot point and crops are irrigated with impact sprinklers or drop nozzles. A typical center pivot irrigation system and its main components are presented in *Figures 1* and *2*. An area centered on the pivot point is irrigated, creating a circular pattern in crops. Most center pivots were initially water-powered but now most are propelled by electricity and diesel motors. Natural gas, propane, and a limited number of ethanol fuel-based engines are also used. The entire main pipeline of the center pivot system is rotated at the same time very slowly around the pivot point in the center of the field by motors (usually 1 HP each) at each tower (span).

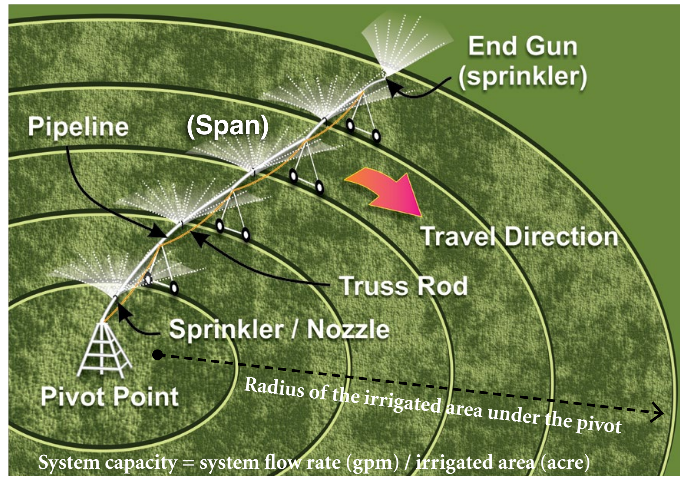

Figure 1: Some of the basic components of a center pivot irrigation system in the field.

Figure 2: A nine-span center pivot system operating in a soybean field in southwestern Nebraska in an early summer morning to assess the uniformity of the water application.

In some cases, towers move incrementally — one tower moves forward for a certain distance and stops and the next tower moves the same distance and stops. This process is repeated for each tower (each tower moves individually).

In some center pivot systems, the entire system (all spans) moves simultaneously and continuously. Sprinklers or nozzles, which are the system components designed to distribute the water to the field uniformly as the center pivot rotates, are mounted on the main system delivery pipe (span).

Center pivot systems are available to cover square fields ranging in size, usually 80 to 260 acres (32.4 to 105 hectare) or larger. Total system capacity usually ranges from 400 to 1,200 gpm (90.85 to 272.55 m^3/hour) or greater. Lateral (linear)-move systems are available to irrigate rectangle fields. Lateral-move systems travel back and forth in the same horizontal direction rather than in a circular direction. The speed of the center pivot is a function of water application rate.

Center pivots function best in flat terrains, which results in minimal surface runoff when the pivot is operated properly and effective irrigation management is practiced. The discharge rate of the sprinklers/nozzles should be smaller than the soil permeability to enable irrigation water infiltration into the soil to prevent surface runoff during the irrigation.

Center pivots can also operate effectively in sloping/rolling fields. When properly designed and managed, center pivots are more efficient in terms of water delivery and uniformity than surface irrigation methods. In some regions of the world, this advantage has resulted in increased irrigated acreage and enhanced crop yield productivity per unit of water applied.

In center pivot irrigation systems, the nozzle or sprinkler size is tapered as the flow rate increases gradually from the first span (from the pivot point) to the outer span to compensate for the increased area to be irrigated per revolution of the center pivot. Advances in nozzle technology have enabled these systems to minimize water losses from drift evaporation during the irrigation (e.g., low drift nozzles).

The typical center pivot system has seven spans each with a typical span length of 160-190 ft (48.8 – 57.9 m). Most center pivots are designed to deliver 1.0-1.25 inch (25.4 – 32 mm) of irrigation water per revolution, although this amount can be easily adjusted with the center pivot speed, depending on the system design capacity. The span length can range from 100-250 ft (32 – 76 m). The area under each span that is irrigated increases substantially from the pivot point toward the end tower (span). The area under each span (based on various span lengths) and discharge rates are presented in *Table 1*.

When a square field is irrigated using a center pivot system, the corners of the field can be irrigated using corner systems or end-guns. When a square-shaped field is irrigated with a center pivot without a corner system, about 21 percent of the total field area is not irrigated. Fertilizers and other nutrients can be applied via a center pivot irrigation system (fertigation). Chemicals can also be delivered at any time during the growing seasons using the center pivots (chemigation).

Crop Water Use Efficiency (Crop Water Productivity): The irrigation effectiveness in terms of crop yield with respect to water use. It is defined as the ratio of the mass of economic yield or biomass produced per unit of water used in evapotranspiration (ET) and it is expressed as:

$$CWU_E = (Yi - Yd) / (ET_i - ET_d)$$

CWU_E = crop water use efficiency (bu/acre-inch)
Y_i = yield of irrigated crop (bu/acre)
Y_d = yield for an equivalent rainfed (dryland) crop (bu/acre)
ET_i = ET for irrigated crop (inch)
ET_d = ET for rainfed (dryland) crop (inch)

The CWU_E equation represents the ratio of the yield increase to the increase of ET under irrigation, relative to rainfed or dryland treatment. Crop water use efficiency has units of production per unit of water used as ET. Units typically used are ton per acre-inch, pound per acre-inch, or bushels per acre-inch.

Table 1: Irrigated field area and discharge rate for a typical center pivot irrigation system (Adopted from the Nebraska Extension Publication "Center Pivot Irrigation Management Handbook," 2011).

Span number (starting from pivot point)	*Cumulative span length (ft)*	*Cumulative area under the span (acre)*	*Cumulative discharge from each span (gpm)*
1	180	2.3	14
2	360	9.3	42
3	540	21.0	71
4	720	37.4	99
5	900	58.4	127
6	1080	84.1	156
7	1260	114.4	184
Including overhang	1310	123.7	56
TOTAL			**749**

CWU_E values can vary substantially for the same crop from one field to another in the same region and between the regions due to differences in management practices. It also has substantial inter-annual variability due to climatic variables impacts on yield and evapotranspiration. In Nebraska, on a statewide average basis, irrigated maize CWU_E ranges from 5.4 bu/in to 8.5 bu/in with a statewide average value of 7.04 bu/in of ET. Soybean CWU_E ranges from 2.1 bu/in to 3.4 bu/in with a statewide average value of 2.09 bu/in of ET.

Deep Percolation: The amount of water that drains vertically below the crop root zone. While in an agricultural field, deep percolation may be considered as a loss of water below the root zone; in other water balance categories it may be considered a source of water that recharges groundwater/aquifer and is not considered a loss. Deep percolation rates vary with the type of irrigation system; irrigation frequency and application amount in each irrigation event; precipitation duration and rate; initial soil water content before soil wetting with irrigation and/or precipitation; crop type; crop water use rate; field slope; crop rooting depth; soil textural and physical characteristics, including infiltration rate and conductivity; management practices' and other factors. Since the crop's root zone varies due to many factors, including crop root characteristics, climatic condition, and management practices, the amount of deep percolation calculated for different crop types in the same soil type can vary.

Deficit Irrigation: An irrigation method that increases or optimizes water use efficiency by eliminating irrigation events during the less sensitive crop growth stages that may have less impact on crop yield/productivity than other more sensitive stages. In many cases, it is not feasible to practice irrigation to meet the full crop water requirement due to limitations in a variety of factors, including availability of water, water withdrawal allocations, high crop water use rates, limitations in irrigation system capacity, soil textural properties (e.g., coarse-textured soils that have limited water-holding capacity), water quality issues, and other reasons. Agronomic measures such as reduced or no-till practices, mulching, and the use of anti-transpirants (crop regulators that reduce transpiration rate via stalling leaf stomata) can reduce irrigation requirements. In such cases, practicing deficit irrigation can increase crop water productivity (crop water use efficiency).

Under water-limiting conditions, deficit irrigation is practiced to apply water at certain crop growth and development stages, which exposes crops to certain (predetermined) levels of water stress during either a particular growth or development stage or throughout the irrigation period during the growing season.

The magnitude of water stress sensitivity varies substantially among different crops and their corresponding growth stages. For example, during the vegetative growth stage, maize grain yield is less affected by water stress than during the more sensitive tasseling, silking, and grain-fill stages. Soybean crop yield decreases more when water deficit occurs during flowering and pod formation/development stages than during vegetative growth. Thus, maize and soybean crops can be exposed to a certain level of water stress in the vegetative stage rather than the more sensitive reproductive stages.

Even though deficit irrigation, in most cases, will result in enhanced crop water productivity (because less water is applied than the full-irrigation requirement), it may result in a yield reduction due to a reduction in transpiration and evapotranspiration rates as a result of leaf stomata response (closure) to water stress. In practice, deficit irrigation most likely results in enhanced crop water productivity due to less water being applied and losses through evaporation, runoff and deep percolation are minimized. Consequently, decrease in transpiration and evapotranspiration rate due to leaf stomata closure to water stress usually results in yield reduction.

The magnitude of the yield reduction will depend on the crop type, the crop's genetic background, the severity of water stress, the timing of the stress during the growing season, climatic conditions, and other factors such as soil textural and physical properties. Soil textural properties play an important role because they dictate soil water storage capacity. Thus, in deficit irrigation, the water holding capacity of the soil must be taken into account.

In sandy soils, plants may experience water stress very fast under deficit irrigation, whereas plants grown on fine-textured (e.g., silt-loam) soils may have adequate time to adjust to low soil water status until the next irrigation and/or rainfall. Therefore, the success of deficit irrigation management is usually greater in fine-textured soils than in coarse-textured soils in the same climatic conditions. Also, the success of deficit irrigation is greater in humid and sub-humid climates where precipitation usually supplements additional water and could coincide with the critical growth stage when water is needed, compared with arid and semi-arid climates.

Drip (Trickle) Irrigation: A form of the microirrigation method, drip irrigation can be either surface drip or subsurface drip. Subsurface drip irrigation (SDI) supplies water directly to the crop root zone via polyethylene drip lines and emitters. Black polyethylene is usually used to prevent algae growth inside the drip line. Irrigation laterals are buried below the soil surface, typically between 8 to 20 inches, depending on the soil and crop type, climate, management practices, and other factors. In sandy or sandy loam soils, drip lines should be buried shallower than those in more finely textured soils (e.g., silt loam, clay loam) and the between row spacing should be narrower than those in heavier textured soils to ensure adequate access of water by the crop roots. The operational characteristics of the surface drip irrigation are essentially the same as SDI, but the drip lines are placed on the surface.

Burying drip lines underground eliminates surface soil evaporation due to irrigation. If properly designed and managed, SDI system eliminates wind drift and surface runoff, reduces surface soil evaporation, minimizes water and nutrient loss due to deep percolation and enables "precision-feeding" the crop through effective delivery of irrigation water and nutrients directly to the crop root zone at any point during the growing season.

The "precision-fed" characteristic of the SDI system has great potential to minimize or eliminate the movement of water and nutrients below the crop root zone when the system is properly managed. With SDI, the irrigation water is filtered at the filter and control station before entering the field through the drip laterals.

Even though drip and trickle irrigation are used interchangeably, the American Society of Agricultural Engineers Practice EP405 makes a technical distinction that trickle irrigation includes water application systems with greater discharge rates than those with drip systems. To be classified as a drip irrigation system, point source emitters should have discharge rate of 3 gph or lesser and line source emitters less than 0.02 gal/hr/ft of irrigation lateral. Trickle irrigation is also considered as a form of microirrigation.

Compared to other irrigation systems, SDI is the most efficient way to deliver irrigation water to the crop root zone with irrigation efficiency usually greater than 95 percent. The lateral and vertical wetting area of the soil takes place inside the soil profile only to a certain extent as a function of soil physical properties and system flow rate, frequency of irrigation applications, and other factors. The water is delivered in small amounts using emitters that are designed to provide low flow rate (discharge) at the atmospheric pressure head at specific discharge points, in spite of system pressure that is maintained at certain levels, usually between 18-22 psi for SDI and lower pressures for surface drip. With a surface drip irrigation system, only a fraction of the soil surface (e.g., 10-50 percent) is wetted, which helps reduce/minimize soil surface evaporation losses.

The *bubbler irrigation* method, which is the application of water to the soil surface as a small stream or form of fountain, also is included in the *trickle irrigation* category. Discharge rates with bubblers are generally greater than those for drip irrigation, but less than 1 gpm (3.78 L/min). The soil surface evaporation losses are usually lower with the subsurface drip irrigation than the surface drip irrigation.

Effective Rainfall (Precipitation): The portion of the total annual or seasonal rainfall, or a portion of any given precipitation event, which is used directly and/or indirectly for crop production. Effective rainfall usually excludes irrigation and/or rainfall water intercepted by green and/or dry vegetation/canopy, water that is lost by evaporation from the soil surface.

Effective rainfall is sometimes defined as the total rainfall minus evapotranspiration. For crop production, the rainfall should infiltrate the soil. Therefore, effective rainfall is sometimes defined as the amount of total rainfall (precipitation) that infiltrates the soil profile.

Even though precipitation and rainfall are used interchangeably in many cases, precipitation includes all forms of water falling to the surface, including rain, snow, sleet, and hail, whereas rainfall usually refers to the liquid water (rain). The effectiveness of rainfall is influenced by many factors, including land/soil physical and chemical characteristics (soil type, slope, residue cover, and other physical and chemical characteristics that influence infiltration rate, etc.); other meteorological conditions (temperature, solar radiation, and wind speed); rainfall characteristics (rainfall duration, rate); soil-water characteristics, soil and crop management practices, drainage characteristics, and crop characteristics, etc.

Effective rainfall can vary substantially for different land cover and land use types, and the interception of rainfall by vegetation/canopy can be a considerable fraction of precipitation, as much as 15-40 percent in forest canopies. In agricultural fields, maize, soybean, and similar crop canopies can intercept 0.08 inch to 0.16 inch of precipitation, sprinkler irrigation water for precipitation, or irrigation events greater than 0.5-0.6 inch.

Evaporation: A transformation of any given substance (i.e., water) from liquid form to vapor (water vapor) form. In a solid (frozen) water case, the evaporation is known as sublimation (i.e., convergence of ice to water vapor). Evaporation can occur from the soil surface, free water surfaces (lakes, ponds, rivers), surface irrigated fields, parks, buildings — essentially from any surface, including crop surfaces as a result of intercepted water from irrigation and/or precipitation.

All these evaporation losses are essential components of the hydrologic cycle. In an agricultural crop production setting, soil evaporation can be a significant fraction of seasonal total crop evapotranspiration, depending on soil, crop, and irrigation management as well as climatic characteristics. Reduced or no-till practices, as well as early planting and narrower row spacing that results in faster canopy closure, can reduce evaporation losses. In the hot and windy conditions of the Midwestern region, soil evaporation can be up to 30-35 percent of seasonal total evapotranspiration of agronomic croplands.

Irrigation management, including irrigation method, irrigation frequency, and application amounts, can have substantial influence on soil evaporation rates. In subsurface drip irrigation, for example, the soil surface can be extremely dry (in the absence of precipitation), and water status can be very close to or at wilting point, crops do not experience any water stress since the roots have ample access to water in deeper layers from drip lines that are buried underground. Therefore, surface soil evaporation from irrigation is minimal.

In surface irrigation methods, the surface evaporation occurs primarily from free surface irrigation water, and it is not a significant fraction of total water applied (i.e., 1-3 percent). Evaporation losses from sprinklers/spray nozzles are a strong function of nozzle/droplet characteristics (type, size, and pressure), air temperature, wind speed, relative humidity, and vapor pressure deficit during the irrigation. Such losses can range from 2 to 10 percent (or more during very hot and windy conditions) of the total amount of water discharged by the sprinklers.

Evapotranspiration (Crop Water Use, Latent Heat Flux): The water loss into the atmosphere, which is the sum of evaporation from any surface plus transpiration from green vegetation (takes place in the form of very small water vapor particles through plant stomata). In practice, separation of evaporation and transpiration is a very difficult task; therefore, these two terms are often combined into the term "evapotranspiration."

In most cases, evapotranspiration is the largest component of the hydrologic cycle in arid, semiarid and subhumid regions. In humid regions, the precipitation amount usually exceeds the evapotranspiration amount. Therefore, accurate quantification of evapotranspiration is critical for accurate/complete water balance analyses, and current and future water use projections on a field, a watershed, a region, or a global scale.

Field Capacity: Represents the practical upper limit of plant-available water in the soil. Field capacity is one of the most critical soil physical characteristics and plays a vital role in soil-water movement, hydrology, plant physiological responses, irrigation/water management, soil moisture dynamics, crop water uptake, evapotranspiration, runoff, deep percolation, and many other processes in agriculture and natural resources settings. It drives many soil-plant-water dynamics. Field capacity of any given soil is a strong function of soil particle size distribution (i.e., percent sand, silt, clay, and organic matter content).

In more technical terms, field capacity is defined as the amount of water held in the soil after excess water (as a result of a heavy rainfall or irrigation event) has freely drained away, and the rate of downward movement of water has materially decreased (negligibly small), which usually takes place within two to three days after a heavy rain or irrigation in pervious soils of uniform structure and texture. Thus, the soil water content in the soil profile two to three days after a heavy rain or irrigation event is considered to be the field capacity. In this definition, it is assumed that any upward movement of the water table does not contribute to soil water status in the soil profile.

Two main reasons for the water movement to become negligibly small are: (i) the hydraulic gradient becomes smaller as the water moves through the soil and the difference in moisture content through the soil profile becomes smaller, and (ii) the conductivity becomes smaller. Either of these factors can result in the soil water movement becoming negligibly small (Hillel, 1998; Hagan et al., 1967).

For practical purposes, the soil water content at 1/10 bar is considered the field capacity for coarse-textured soils (sandy, sandy loam), and water content at 1/3 bar is considered the field capacity for fine-textured soils. However, it is important to note that not all soils will result in free drainage of soil water two to three days after a rain or irrigation event. Therefore, in real field conditions, the 1/10 or 1/3 bar field capacity values are not constant for a given soil type.

One of the best options to determine field capacity of a given soil is to measure soil water content two, three, four, and five days after a heavy rain or irrigation event in the field and determine when the change in soil water content becomes very small or negligible. This value can be considered a field capacity for this soil. Furthermore, since soil textural properties change with soil layers, this process can be conducted for different soil layers to determine layer-specific field capacity values for a given soil.

Gravitational Water: The amount of water that temporarily exists between saturation point and field capacity. After a heavy rainfall or irrigation event, the soil profile may be filled to field capacity. If further rainfall or an irrigation event occurs, the soil water status can exceed field capacity (but less than saturation), which is generally referred to as gravitational water.

Gravitational water moves in the soil profile due to gravitational forces only. This water moves rather rapidly and is considered to be unavailable for plant uptake. Thus, gravitational water is not and should not be included in irrigation management, evapotranspiration, and crop water requirement determinations. Gravitational water must be removed first by drainage, movement to deeper soil layers, and/or evaporation before soil attains its field capacity soil water status and plants start using soil-water.

While gravitational water is not accounted for directly in irrigation and evapotranspiration-related calculations, it does influence irrigation requirement determinations indirectly. For example, after a heavy rainfall event, gravitational water can delay an irrigation trigger point because this excess water has to be removed first before plants start using soil-water that is held at or below field capacity matric potentials and/or water evaporates before reaching drier conditions to trigger the next irrigation.

Gravitational water is present in the soil at matric potentials (suctions) less than field capacity (i.e., matric potentials between zero and 10-33 kPa). Matric potential indicates the energy that must be spent by the plants to extract water from the soil. Once the energy is quantified, this information can be effectively used for irrigation management. When soil water is extracted by plants, the most readily available water is removed first.

A schematic representation of gravitational water, temporary surface storage, field capacity, permanent wilting point, etc., is presented in *Figure 3*. After gravitational water is drained through the soil profile, the water status is close to the field capacity and plants can start to uptake.

Since the temporary gravitational water existing in the soil is a strong function of soil particle size distribution (i.e., percent silt, clay, sand), and in turn, saturation and field capacity values of the soil, it varies substantially between different soil types. Soil saturation point, field capacity, and gravitational water for various soil types are tabulated in *Table 2*.

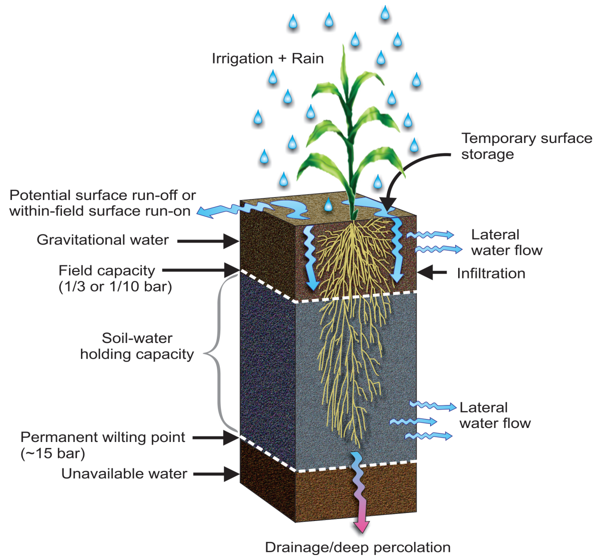

Figure 3: Schematic representation of some of the main soil-water, hydrologic, and related variables in a typical agricultural soil profile.

Table 2: Tabulated values of saturation point, field capacity, and gravitational water for various soil types [values are calculated using procedures outlined by Saxton et al. (1986) and Saxton and Rawls (2006)].

Soil type	*Saturation (inch/ft)*	*Field capacity (inch/ft)*	*Gravitational water (inch/ft)*	*Plant available water (inch/ft)*
Sand	5.50	1.10	4.41	0.27
Loamy sand	5.36	1.49	3.87	0.50
Sandy loam	5.30	2.20	3.11	0.96
Loam	5.41	3.15	2.26	1.62
Sandy clay loam	5.10	3.34	1.76	1.32
Silty loam	5.66	3.60	2.06	2.36
Silt	5.69	3.73	1.96	2.40
Clay loam	5.59	4.15	1.44	1.85
Sandy clay	5.22	4.32	0.90	1.62
Silty clay loam	6.02	4.48	1.55	2.20
Silty clay	6.31	4.91	1.39	1.71
Clay	5.86	4.96	0.90	1.68

Coarse-textured soils have lower water holding capacity than the fine-textured ones. Coarse-textured soils, in general, have a lower saturation point and field capacity. However, since the saturation point of sandy soils is not substantially lower than those of fine-textured ones, the difference between saturation point and field capacity, which is gravitational water, is greater for the coarse-textured soils than that for the fine-textured soils.

As soil texture moves from coarse to fine, the field capacity and saturation point increases and the difference between the two decreases proportionally. Therefore, as the soil texture moves from coarse to fine, the amount of gravitational water decreases, which is shown in *Figure 4*.

Plant available water (the difference between field capacity and permanent wilting point), values for each soil type are also included in *Figure 4* and *Table 2*. For example, sandy soil has a saturation point of 5.5 inch/ft, field capacity of 1.1 inch/ft, and, therefore, gravitational water of 4.4 inch/ft; whereas one of the finest-textured silty clay soils has only 1.4 inch/ft of gravitational water (*Figure 4*). While gravitational water is temporary, moves fast, and is not available for plant uptake, the amount of this temporary gravitational water has important implications for surface infiltration, runoff, and deep percolation that can occur from the field. Since the soil textural properties can have vertical spatial variability, the amount of gravitational water can vary with vertical soil depth as well.

Hydraulic Conductivity: The capacity or ability of soil to allow water to pass through the pores or voids within the soil. In technical terms, hydraulic conductivity is the ratio of the soil water flux to the potential gradient (slope of the water flux vs. gradient curve), which has the dimensions in length over time (Hillel, 1998). It is a critical soil variable that influences many processes, including soil water and chemical/nutrient movement.

Hydraulic conductivity is affected by soil structure as well as soil textural characteristics. If the soil is highly porous, fractured, or aggregated, it will have much greater hydraulic conductivity than the compacted and dense soils. In addition to soil porosity, hydraulic conductivity is greatly influenced by soil pore size and distributions. For example, gravel or coarse sandy soils with large pores can have much greater hydraulic conductivity value than a clay soil with small pore size, even though the total porosity of a clay soil is usually larger than sandy soils.

Cracks, root channels, and worm holes in the soil structure can substantially affect the hydraulic conductivity value. Since soil structure can vary greatly within the same field, the hydraulic conductivity also varies substantially within the same field. In fact, hydraulic conductivity is one of the most spatially variable soil hydraulic properties. Soil hydraulic conductivity measured within several feet in the same field can vary considerably.

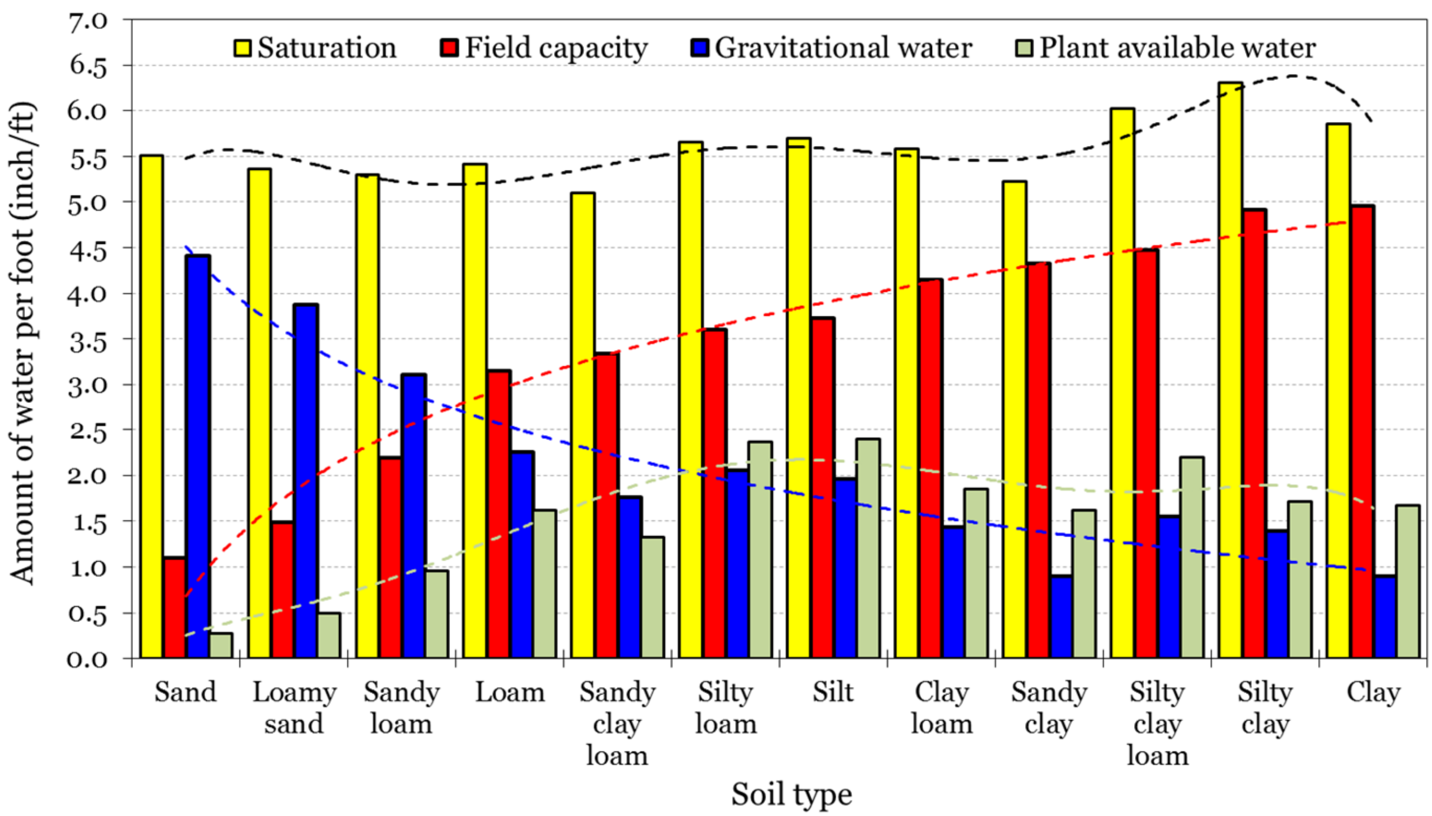

Figure 4: Amount of water (inch per foot) at saturation, field capacity, and the amount of temporary gravitational water [values are calculated using procedures outlined by Saxton et al. (1986) and Saxton and Rawls (2006)].

Since soil water movement can occur in essentially two distinct environments, saturated (near saturation) and unsaturated, the hydraulic conductivity is also subdivided into saturated hydraulic conductivity and unsaturated hydraulic conductivity. Even though, in general, it is extremely difficult to saturate the soil in the field conditions without trapping air, the term saturated hydraulic conductivity is often used. In field conditions, the more accurate or descriptive term would be *near-saturation* rather than *saturated* (or *satiated*).

Soils can be forced to be saturated in laboratory conditions by applying pressure to remove all the air out of a soil sample while measuring saturated hydraulic conductivity. Saturated hydraulic conductivity is very small in near-saturated soils, but it is seldom a constant value and has a diminishing value over time. Saturated hydraulic conductivity of soils can range from 10^{-10} to 10^{-8} m/sec for clay soils; from 10^{-8} to 10^{-6} m/sec for silt; from 10^{-5} to 10^{-1} m/sec for sand; and from 10^{-2} to 10^{-1} m/sec for gravel.

Unsaturated hydraulic conductivity value is much smaller than saturated hydraulic conductivity for a given soil. Agricultural soils of the Midwestern and Western United States have hydraulic conductivity values ranging from 0.05 inch/hr to 5 inch/hr or greater. However, some clay soils can have hydraulic conductivity as low as 0.005 inch/hr, but can still be very productive (Hillel, 1998).

Hygroscopic Water: Water absorbed from the atmosphere and held very tightly by the soil particles, so that it is unavailable to plants in amounts sufficient for them to survive. After soil water between field capacity and permanent wilting point is depleted, soil becomes very dry and extracting water molecules from soil particles by the plants becomes very difficult. When further drying occurs, the soil becomes extremely dry. However, even if soil is extremely dry, there is still some soil water in the soil, but it is bounded in the soil particles at very high matric potential.

The hygroscopic water is held by the soil particles at matric potentials (suctions) greater than 3,000 kPa (30 bars; 29.6 atm; 435 psi). Even if the soil is dried in the oven at 105°C (221°F) until it reaches a constant weight, residual water can still remain bounded in the soil particles (Hillel, 1998). Hygroscopic water is sometimes referred to as residual water. It is also referred to as unavailable water (*Figure 3*).

Hysteresis (desorption and sorption): The relationship between soil matric potential and soil water content, which is described as soil-water retention curve (described in detail in *Figure 7*) to convert matric potential to water content or vice versa., It can be obtained in two distinct ways: (i) the soil column can be wetted to near-saturation and as the soil drying cycle continues, the values of matric potential and water content are measured simultaneously from near-saturation to the dry soil range. This process is called *desorption* (drying cycle); (ii) another process starting with initially dry soil and soil matric potential, and water content values are measured simultaneously as water is added to the soil column. The soil is wetted to bring soil water content to certain levels each time and wetting the soil continues until it reaches near saturation. This process is called *sorption* (wetting cycle).

Both procedures can yield measurement of continuous soil-water retention curve. Soil-water retention curves can be different with desorption and sorption procedures. The equilibrium soil water content at a given matric potential is usually greater in desorption than in sorption, and this is called *hysteresis* or *hysteresis effect* (Hillel, 1998).

The rate at which water percolates into soil. In most cases, the infiltration rate is much higher at the beginning of an irrigation and/or rainfall event and decreases gradually over time as the soil gets wetter.

Infiltration is substantially influenced by soil physical properties as well as soil moisture gradient. Moisture tension (matric potential) of the topsoil can be zero or near-zero (very close to saturation point) in the first 1 or 2 inches of topsoil right after rainfall or irrigation, but can be very high (dry) in several inches below the surface, creating a substantial downward gradient forcing the water to percolate into this unsaturated soil layer. In this case, the infiltration rate is high. This process enables water to penetrate/infiltrate the soil.

After water infiltrates the soil, the infiltration process is not immobile, but water may not move as fast in the soil profile as the rate when it entered it. Water continues to move through the soil profile as a function of various forces.

Several hours after infiltration, this process slows down as the deeper soil layers get wetter and the gradient decreases. Therefore, the infiltration rate becomes small.

The knowledge of the decrease in infiltration rate with time after wetting a soil is critical for developing effective irrigation management, through selection of appropriate water application rates; rainfall vs. runoff studies, etc. Generally, the infiltration rate is highest for initially dry sandy soils and lowest for wet clayey soils, especially if the soil surface is compacted (Hillel, 1998).

A typical pattern of infiltration rates as a function of time for various soil textures is presented in *Figure 5*. As previously stated, the amount of water that will infiltrate a homogenous soil in a unit time decreases as the amount of water that has already percolated into the soil increases. Therefore, typical curves relating infiltration rate to time are not linear. As the water percolation continues, the infiltration rate approaches a constant value, which is a robust indicator of infiltration rate.

As indicated in *Figure 5* and presented in *Table 3*, infiltration rates vary significantly from one soil texture to another. When the soil is saturated, the rate of infiltration of water through the soil profile in a vertical downward domain is essentially numerically equal to the soil's hydraulic conductivity value to a sufficient depth (i.e., 120-140 min infiltration rates in *Figure 5*). In this case the gradient of water flow is only (or mostly) influenced by gravity force. As the soil dries out again, the infiltration rate may substantially exceed the hydraulic conductivity (Hillel, 1998).

Irrigation: The unnatural methods of application of water, in the absence of sufficient precipitation and stored soil moisture, to a soil surface or subsurface for the purpose of supplying the water essential to plant growth and development and yield and/or biomass production. The Latin origin of the term "irrigation" is "irrigationem," which means watering.

In humid and subhumid areas, irrigation is (or should be) practiced as a supplementary supply of water in addition to precipitation, especially during critical crop growth and development stages in which precipitation is insufficient to meet crop water requirements. Irrigation in arid and semiarid climates is often a requirement, rather than supplementary, to produce grain yield due to lack of rainfall for crop production.

Other irrigation uses include cold/freeze protection, leaching of salts, dust control, mining operations, wetting of dry row middles to control dust and prevent sand/silt/crop residue from blowing during windy conditions, and other environmental controls.

Irrigation can also be practiced to alter microclimatic conditions during extreme conditions. For example, in extremely hot weather conditions, center pivot irrigation can be practiced even if there is enough soil moisture in the soil profile, with a small (0.15-0.20 inch), quick water application to cool down the crop canopy to mitigate the impact of extreme heat stress on crops. This can be beneficial especially during the silking/pollination stage for maize when extreme heat stress can cause kernel abortion, resulting in reduction in grain yield quantity and quality. Irrigation is also practiced to deliver certain fertilizers (*fertigation*) and other chemicals (*chemigation*) to the crop canopy or soil.

Irrigation Application Uniformity: Measure of how uniformly water is distributed with the irrigation system to achieve maximum benefit from the water applied. The uniformity of irrigation application depends on many factors that are related to the method of irrigation, topography, soil (infiltration) characteristics, and pressure and flow rate of the irrigation system. For a sprinkler irrigation system, nonuniformity can be due to numerous factors: (i) improper selection of delivery pipe diameters (sub-main, manifolds, and lateral), (ii) too high or too low operating pressure, (iii) improper selection of sprinkler heads and nozzles, (iv) inadequate sprinkler overlap, (v) wind effects on water distribution, (vi) wear and tear on system components with time, such as pump impellers, pressure regulators, or nozzle size, and (vii) nozzle clogging.

For surface irrigation, nonuniformity can be caused by: (i) differences in opportunity time for infiltration caused by advance and recession, (ii) spatial variability of soil-infiltration properties, and (iii) nonuniform grades. For microirrigation, nonuniformity can be due to: (i) variations in pressure caused by pipe friction and topography, (ii) variations in hydraulic properties of emitters or emission points (from clogging or other reasons), (iii) variations in soil wetting from emission points, and (iv) variations in application timing. For all irrigation methods, poor management can also cause nonuniformity.

Table 3: *Typical* or *average* infiltration rates for different soil types (Free et al., 1940; Hillel, 1998).

Soil type	*mm/hr*	*in/hr*
Sand	>30	1.18
Sandy-loam	30-20	1.18-0.79
Silty-loam	20-10	0.79-0.39
Clay-loam	10-5	0.39-0.2
Clay	<5	0.2

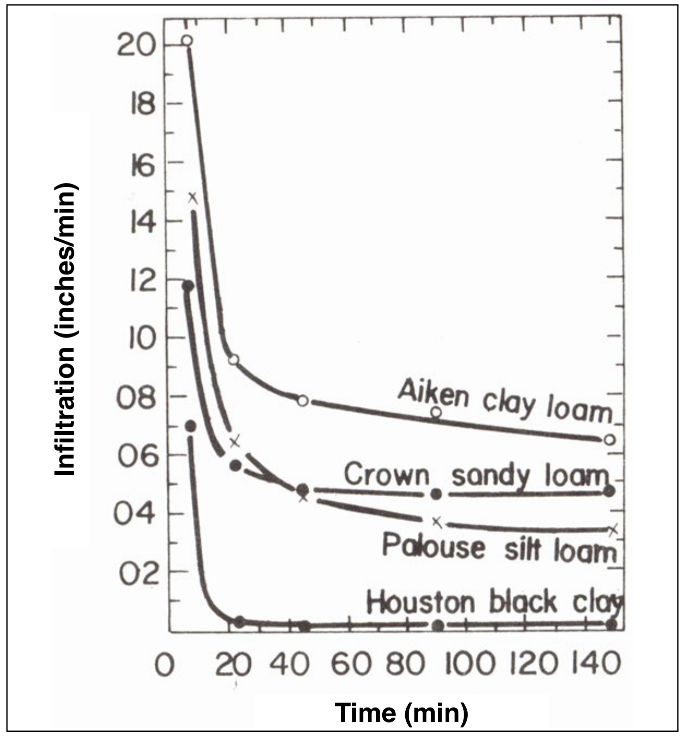

Figure 5: Infiltration rate as a function of time for various soil types (from Free et al., 1940).

Generally, irrigation uniformity is calculated based on indirect measurements. For example, the uniformity of water that enters the soil is assumed to be related to that collected in catch cans for sprinkler systems, to intake opportunity time and infiltration rates for surface systems, and to emitter discharge for microirrigation systems. The common uniformity measures for sprinkler, surface, and microirrigation systems are described in the next section.

Christiansen's Uniformity Coefficient (C_u) for Sprinkler Irrigation Systems

Christiansen's Uniformity Coefficient (C_u) is commonly used to describe uniformity for stationary sprinkler irrigation systems and is based on the catch volumes (or depth):

$$C_u = 100\ [1 - (\sum|X_i - X_m|) / \sum X_i]$$

C_u = Christiansen's uniformity coefficient (%)
X_i = measured depth water in equally spaced catch cans on a grid arrangement (inch)
X_m = mean depth of water of the catch in all cans (inch)
$\sum$ = indicates that all measured depths are summed (inch)

The C_u method assumes that each can represents the depth applied to equal areas. This is not true for data collected under center pivots where the catch cans are equally spaced along a radial line from the pivot to the outer end. For center pivot systems, it is necessary to adjust and weigh each measurement based on the area it represents.

Adjusted Uniformity Coefficient ($C_{u(a)}$) for Center Pivot Irrigation Systems

The adjusted uniformity coefficient for center pivots reflects the weighted area for catch cans that are uniformly spaced and thus represent unequal land areas:

$C_{u(a)}$ = $100[1-((\sum S_i V_i - (\sum V_i S_i/\sum S_i))/\sum(V_i S_i))]$
$C_{u(a)}$ = adjusted uniformity coefficient for center pivots (%)
S_i = distance from the pivot to the i^{th} equally spaced catch container (ft)
V_i = volume of the catch in the i^{th} container (inch)

Low-Quarter Distribution Uniformity (D_U) for Surface Irrigation Systems

The distribution uniformity is more commonly used to characterize the irrigation water distribution over the field in surface irrigation systems, but it can also be applied to micro and sprinkler irrigation systems. The low-quarter distribution uniformity (D_U) is defined as the average depth infiltrated in the low one-quarter of the field divided by the average depth infiltrated over the entire field and is expressed as:

$$D_U = (D_{lq} / D_{av}) \text{ x } 100$$

D_U = distribution uniformity (%)
D_{lq} = average depth of water infiltrated in the low one-quarter of the field (inch)
D_{av} = average depth of water infiltrated over the field (inch)

Typically, D_U is based on the post-irrigation measurement of water depth that infiltrates the soil because it can be more easily measured and better represents the water available to the crop. Usually, for the water depth measurements, it is recommended to monitor the time it takes for the water to reach different points chosen in the field along the furrow and the recession time at the same positions. Different models can be used to estimate the infiltrated depth along the furrow. Thus, there is no sampling within the field. For basin irrigation, the depth of standing water is monitored at several points in the field and used for D_U estimation and mapping water depth. It also is used to estimate the efficiency of the system relative to the recommended standing water depth at a given growth stage of the crop. Using post-irrigation measurements of infiltrated water to evaluate D_U ignores any water intercepted by the crop and evaporated, and any soil water evaporation that occurs before the measurement. Any water that percolates below the root zone or the sampling depth will also be ignored. A low D_U (≤60 percent) indicates that the irrigation water is unevenly distributed, while a high D_U (≥80 percent) indicates that the application is relatively uniform over the entire field. D_U values less than 60 percent are generally considered low, and a D_U value greater than 75 percent is considered satisfactory by some researchers.

Emission Uniformity (E_U) for Microirrigation System

For microirrigation systems (trickle, surface drip, subsurface drip, microspray), both C_U and D_U concepts are impractical because the entire soil surface is not wetted. Microirrigation uniformity is affected by the variability in emitter discharge rates. This variability can be caused by manufacturing variations in orifice size and shape, clogging of the orifices, topographic factors, and hydraulic characteristics of the irrigation system. Uniformity of irrigation water application in microirrigation systems is defined by emission uniformity (E_U) expressed by the empirical formula:

$$E_U = [[1 - 1.27 (C_{vm}) n^{-1/2}] (q_{min} / q_{avg})] \times 100$$

E_U = emission uniformity (%)
C_{vm} = manufacturer's coefficient of uniformity (unitless)
n = the number of emitters per plant
q_{min} = minimum emitter discharge rate at minimum system pressure (gpm)
q_{avg} = average emitter discharge rate (gpm)

The above definition of E_U is based on the ratio of the discharge rate for the lowest quarter of emitters to the average discharge rate, and includes the influence of multiple emitters per plant so that each may have a flow rate from a population of random flow rates based on the emitter variations from manufacturing.

Coefficient of Design Uniformity (C_{Ud}) for Microirrigation Systems

Another parameter commonly used to evaluate the uniformity of water distribution in microirrigation systems is the coefficient of design uniformity (C_{Ud}), which is based on the emitter discharge rate deviations from the average rate:

$$C_{Ud} = [(1 – 0.798(C_{vm})n^{-1/2})] \times 100$$

C_{Ud} = coefficient of design uniformity (%)
C_{vm} = manufacturer's coefficient of uniformity
n = number of emitters

Irrigation Efficiency: The ratio of water stored in the plant root zone to the water supplied or diverted to the field. Irrigation efficiency is not a constant number and can change throughout the growing season. It is also a strong function of how irrigation systems are managed.

Irrigation Requirement: The amount of water needed for plant growth and development, and yield production. It is the difference between crop evapotranspiration and effective rainfall plus any soil water storage in the soil profile from spring/winter precipitation.

Because most crop production systems have soil evaporation components that cannot be totally eliminated, evaporation is always a part of the irrigation requirement. When soil evaporation is reduced or minimized in cases in which crop production is under reduced or no-till soil management or a subsurface drip irrigation system, the irrigation requirement of the crops under these conditions will be lower than the irrigation requirement of the same crop grown under disk-till or gravity (furrow) or sprinkler irrigation.

Irrigation Water Use Efficiency (IWU_E): Used to characterize crop yield in relation to total depth of water applied for irrigation. It is expressed as:

$$IWU_E = (Y_i – Y_d) / IR_i$$

IWU_E = irrigation water use efficiency (bu/acre-inch)
Y_i = economic yield of the irrigation level crop (bu/acre)
Y_d = economic yield for an equivalent rainfed crop (bu/acre)
IR_i = depth of irrigation water applied (inch)

CWU_E is a better indicator than irrigation water use efficiency when quantifying the efficiency of a crop production system. This is because it directly reflects the amount of grain yield produced per amount of water used rather than per depth of water applied, which is the case with the IWU_E. This also is because not all irrigation water applied to the field is used for crop ET, especially in humid and subhumid areas. Thus, IWU_E does not account for the irrigation application losses and actual water used by the crop in arid and semiarid climates. However, the probability of most or all irrigation water to be used for ET is greater than in humid and subhumid regions.

Leaching: The downward movement of water carrying any dissolved particles such as nutrients and/or chemicals/pollutants through the soil profile.

Leaching Requirement: The fraction of irrigation water above the crop water requirement that is needed to leach the accumulated salts in the soil profile and/or crop root zone. The leaching requirement, LR, is an estimate of the amount of water leaching required to maintain soil water salinity within acceptable/tolerable levels to prevent or minimize yield reduction due to salinity. Its calculation is based on the salt and water balance in the crop root zone, but does not consider the solute movement process in the soil. The leaching requirement is dependent on the salt concentration of the irrigation water (EC_{iw}) and that of drainage water salt concentration (EC_{dw}). If the irrigation water is given in the equivalent depth of D_{iw} and the drainage water is given the equivalent depth of D_{dw}, the leaching requirement can be calculated as (all salinity units are in mmho):

$$LR = (D_{dw} / D_{iw}) = (EC_{iw} / EC_{dw})$$

The irrigation depth is also related to consumptive water use (evapotranspiration) depth as:

$$D_{iw} = D_{cw} + D_{dw}$$
$$D_{iw} = [D_{cw}/(1 - LR)] = [EC_{dw} / (EC_{dw} - EC_{iw})] \times D_{cw}$$

The salt tolerance of a given crop as well as yield reduction vs. salt concentration is a strong function of the genetic attributes of the crop. Consequently, the maximum allowable salt concentration in the crop root zone is dictated by the salt tolerance of the crop.

For low frequency irrigation applications, it is suggested that:

$$LR = EC_{iw} / (5xEC_e - EC_{iw})$$

where EC_e is the salt concentration that causes 10 percent yield reduction. For high frequency sprinkler or microirrigation (e.g., drip, microjects, micro-sprinklers, etc.):

$$LR = EC_{iw} / 2 \text{ x } (\max EC_e).$$

Crops have substantially different tolerance levels to soil and water salinity. For example, while barley (one of the most salt-tolerant crops) can tolerate soil (EC_e) and water (EC_w) salinity levels of 8.0 and 5.3 mmhos/cm, respectively, for 100 percent yield potential, maize can only tolerate EC_e of 1.7 mmhos/cm and EC_{iw} of 1.1 mmhos/cm for achieving 100 percent yield potential. Soybean is more tolerant to salt than maize and can handle EC_e of up to 5.0 and EC_{iw} of 3.3 mmhos/cm for achieving 100 percent yield potential.

When the EC_e reaches 18.0, 5.9, and 7.5 mmhos/cm for barley, maize, and soybean, respectively, they start losing 50 percent of the yield potential under these extreme soil salinity conditions. Sugarbeet is another salt-tolerant crop. It can tolerate up to 7.0 mmhos/cm of soil salinity and maintain 100 percent yield potential. The 50 percent yield reduction EC_e level for sugarbeet is 15 mmhos/cm. Wheat is also tolerant to salinity and can handle up to 6.0 mmhos/cm salinity level before losing any yield. The 50 percent yield reduction EC_e for wheat is 13.0 mmhos/cm.

Limited Irrigation: Similar to deficit irrigation, limited irrigation is practiced in water-limiting conditions when complete crop evapotranspiration demand cannot be met. The primary goal of limited irrigation (similar to deficit irrigation) strategies is to maximize or optimize yield or biomass productivity and/or crop water productivity (crop water use efficiency) per unit of water applied or per unit of water used (evapotranspiration or transpiration) under water-limiting conditions.

Even though limited irrigation is also a form of deficit irrigation, it differs from deficit irrigation in that the crop is exposed to an equal amount of water stress at all growth and development stages throughout the growing season, whereas with deficit irrigation the crop is exposed to water stress during certain growth and development stages. Thus, limited irrigation strategy distributes the total seasonal irrigation water available with fixed (predetermined) amounts (e.g., 80 percent, 75 percent, 60 percent, or 50 percent of the full irrigation amount) throughout the growing season, independent of crop growth and developmental stages. For example, if the 75 percent of fully-irrigated strategy is practiced, the seasonal available irrigation water is 6 inches, and six irrigation events are scheduled, the crops receive a total of 0.75 inch of water in each irrigation regardless of crop growth stages.

Similar to deficit irrigation management, the success of the limited irrigation strategy is a strong function of soil textural characteristics (i.e., soil water holding capacity), which makes this strategy more successful in fine-textured soil with greater soil water holding capacity than in coarse-textured soils that have limited soil-water holding capacity (sandy, sandy-loam). Also, since the water allocation amount is divided equally in each irrigation, in certain critical stages of growth, crops may not receive an adequate amount of irrigation water to maximize yield production. Therefore, the limited irrigation strategy has greater potential to be successful in areas with supplemental rainfall (subhumid, humid areas) rather than arid and semiarid regions.

Since the relationships between various crop types and limited irrigation management can be substantially different; and since different crops can have different sensitivity and yield response to different stress levels; and since all these relationships change with the general rainfall pattern during the growing season with locations, developing local limited irrigation crop response to water relationships is critical. When limited irrigation is practiced, the crop yield and water use efficiency depend heavily on the in-season rainfall timing and amount, and the soil-water recharge/storage from spring/winter precipitation.

Management Allowable Deficit or Depletion (MAD): The percentage of the available water in the crop root zone (i.e., field capacity) that can be allowed to be taken up by plants before the next irrigation is required without putting crops under water stress. Also known as allowable water depletion before crop stress occurs, MAD is primarily a function of crop type, soil type, management practices, and climate. For high cash value crops, MAD may be 30 percent or less to maintain a high productivity level.

For lower value or large orchard crops (such as trees), MAD of 60 percent is a usual practice, whereas MAD of 40 percent is a reasonable value for most row crops. MAD should be set up carefully as a function of irrigation well and irrigation system capacity, soil water holding capacity, crop water requirement, and other factors.

Historically 50 percent was applied as a MAD for maize, soybean, and other row crops when surface irrigation was a dominant method of irrigation. However, with increased use of pressurized irrigation systems such as center pivot, drip irrigation, low pressure irrigation, etc., MAD should be set to a value that is lower than 50 percent. This is because it is not feasible to deliver certain amounts of water with the pressured irrigation systems as fast as those with the surface irrigation systems.

For example, the MAD for maize crop can be set to 35-40 percent so that irrigations can be triggered at that level. Since it takes about three to five days for the center pivot to complete the revolution (depending on the system capacity), by the time the pivot completes the revolution the rest of the field would not be stressed more than the 50 percent MAD level. Thus, the time required to deliver certain amount of irrigation water for a given irrigation system must be taken into account when setting the MAD for a given crop. MAD can be set higher during the vegetative growth period (50-55 percent) and should be lower (35-40 percent) during reproductive growth stages, because, in general, agronomic crops are more sensitive to water stress during reproductive stages.

Microirrigation: A frequent and small quantity application of water in the form of droplets, very small streams, or in the form of jet spray or microjects through emitters placed along an irrigation lateral or water delivery line. Microirrigation encompasses several irrigation methods or concepts such as bubbler irrigation, subsurface and surface drip irrigation, trickle irrigation, mist irrigation, and spray, spinner, or microjets. Microirrigation offers unique and flexible agronomic water conservation advantages, as well as frequent, real-time, and very small amounts of water, nutrients, and chemical delivery features.

Spray and spinner emitters and microjects are very often used in microirrigation systems as they enable distribution of water in a wide-diameter fashion. This characteristic is usually desirable in coarse-textured soils where lateral movement of soil water is limited and vertical movement is dominant. The greater surface area coverage allows a large portion of the crop root zone to be wetted by irrigation, which may aid in achieving good water application uniformity as well as potentially better nutrient and water uptake and good root growth and development.

The large wetting pattern of spinners and spray emitters provides advantages when applying herbicides, fungicides, nematicides, insecticides, or fertilizers via an irrigation system. Commonly used spray emitters usually have slotted caps or deflector plates that typically distribute water in distinct stream patterns. Spinners use a moving part that rotates to disperse the water stream over the wetted area. Microirrigation spray and spinner emitters are generally characterized as having operating pressure of less than 30 psi (207 kPa), discharge (flow) rates between 5 to 25 gph (20 to 100 L/h), and throw diameters ranging from 5 to 30 ft (1.5 to 10 m) (Bowman, 1989; Izuno and Haman, 1995).

Permeability: The velocity of water flow caused by a unit hydraulic gradient (difference). In the most simplistic terms, the permeability of soil to water flow is a velocity having the physical dimensions of length divided by time. The velocity of water flow through the soil medium and the pore space is a result of several forces, and permeability is an indicator of this process.

Unlike infiltration, permeability is not influenced by the hydraulic slope. While permeability refers to water flow through the soil *in any direction*, infiltration describes the movement of water in the soil *in a vertical direction*. Permeability is primarily influenced by the physical properties of the soil, while soil temperature influences permeability to a minor extent.

In near-saturated agricultural soils, permeability varies substantially from about 1 ft per year in compacted clay soils to several thousand ft per year in very coarse-textured (i.e., gravel) formations. In unsaturated agricultural soils, soil water status is one of the most influencing factors on the rate of permeability (Hillel, 1998).

Permanent Wilting Point (PWP): The soil water content at which soil cannot supply water at a sufficient rate to keep pace or maintain the turgidity of the plants, and thus, plants permanently wilt. It is also defined as the amount of soil water that exists in the soil when the crops are unable to recover from severe water stress (Hillel, 1998; Hagan et al., 1967).

In addition to field capacity, permanent wilting point is another extremely critical soil physical characteristic that plays a vital role in many soil-water and chemical movements, hydrology, plant physiological responses, irrigation/water management, soil moisture dynamics, crop water uptake, evapotranspiration, run-off, deep percolation, and many other processes in agriculture and natural resources settings. It drives many soil-water processes. While the field capacity defines the upper limit of available water, permanent wilting point defines the lower limit of available water for a given soil.

When the soil water status reaches the wilting point and plants permanently wilt, the result is irreversible damage to plants' physiological and biophysical functions, which means they will not recover from this damage even if the soil water deficit is replenished with irrigation and/or rainfall. In practical applications the soil water content held at 15 bar of tension (suction) is considered as the permanent wilting point value. Even though different crops can have different tolerance to extreme water stress and, in turn, wilting occurs at different soil water status, for most agronomic crops, the soil water content at 15 bar tension is universally accepted and used as the permanent wilting point. In addition to the genetic characteristics that enable most desert plants such as cactus to survive extreme heat and dry conditions, another major reason they can survive extreme drought is that they can also extract water molecules from soil particles in extremely dry soils at soil matric potentials up to 50 bars (725.2 psi; 5,000 kPa; 49.35 atm; 37,503 torr).

Readily (Easily) Available Water (RAW): The amount of water in the crop root zone that can be "easily" or "relatively easily" extracted by the crop. RAW is the *"fraction" of the amount of water held in the soil between field capacity and permanent wilting point* that crops can uptake without experiencing any water stress. Theoretically, most crops can use all the water between the field capacity and wilting point, but soil water availability to plants, in general, decreases with decreasing soil wetness. As a result, plants may experience water stress and reduction in plant growth and development, and yield before the soil water status reaches permanent wilting point. If this happens, the plants will wilt and lose their turgidity, and will experience irreversible damage. Thus, to prevent water stress, irrigations are usually scheduled when a fraction of the water between field capacity and permanent wilting point is depleted.

The suggested ranges of soil matric potentials for triggering irrigations for various soil types are presented in *Table 4*. Since different soil textures have different field capacity and permanent wilting point values, plant available water varies substantially for different soil types.

Table 4: Depletion (inch per ft) in available soil water holding capacity versus soil matric potential; available water holding capacity; and suggested irrigation trigger points for different soil textures (N/A: water not available) (Irmak et al., 2014). Some of the soil matric potential vs. volumetric soil water content values were calculated using the procedures outlined by Saxton et al. (1986) and Saxton and Rawls (2006)].

Soil matric potential (kPa)	*Soil type, depletion in inches per foot associated with a given soil matric potential value measured by the Watermark soil matric potential sensors, and available water holding capacity for different soil types*							
	Silty clay loam topsoil, Silty clay subsoil (Sharpsburg)	*Silt-loam topsoil (Keith)*	*Upland silt loam topsoil, Silty clay loam subsoil (Hastings, Crete, Holdrege)*	*Bottom land silt-loam (Wabash, Hall)*	*Fine sandy loam*	*Sandy loam*	*Loamy sand (O'Neill)*	*Fine sand (Valentine)*
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.20	0.30	0.30	0.30
33	0.20	0.14	0.00	0.00	0.55	0.50	0.45	0.55
50	0.45	0.36	0.32	0.30	0.80	0.70	0.60	0.70
60	0.50	0.40	0.47	0.44	1.00	0.80	0.70	0.70
70	0.60	0.50	0.59	0.50	1.10	0.80	0.80	0.80
80	0.65	0.55	0.70	0.60	1.20	1.00	0.93	1.00
90	0.70	0.60	0.78	0.70	1.40	1.20	1.04	N/A
100	0.80	0.68	0.85	0.80	1.60	1.40	1.10	N/A
110	0.82	0.72	0.89	0.88	N/A	N/A	N/A	N/A
120	0.85	0.77	0.91	0.94	N/A	N/A	N/A	N/A
130	0.86	0.82	0.94	1.00	N/A	N/A	N/A	N/A
140	0.88	0.85	0.97	1.10	N/A	N/A	N/A	N/A
150	0.90	0.86	1.08	1.20	N/A	N/A	N/A	N/A
200	1.00	0.95	1.20	1.30	N/A	N/A	N/A	N/A
Water holding capacity (in/ft)	1.8-2.0	1.8-2.0	2.20	2.00	1.80	1.40	1.10	1.00
***Suggested range of irrigation trigger point (kPa)**	75-80	80-90	90-110	75-80	45-55	30-33	25-30	20-25

(*) The trigger points were calculated with the assumption of no sensor malfunction based on the 35 percent depletion of the total soil water holding capacity per foot of soil layer. The sensor readings and the suggested trigger points should be verified/checked against the crop appearance in the actual field conditions during the season. The trigger point should be the average of the first 2 ft of sensors prior to crop reproductive stages and 3 ft once the crop reaches the reproductive stage (i.e., average of top 2 ft sensors before tassel and average of top 3 ft sensors after tassel for corn). However, for sandy soils, the average of the top two sensors should be used as a trigger point throughout the growing season. *The suggested trigger points are for normal operating conditions. These values should be adjusted (lowered) based on well and irrigation system capacity to be able to keep up with the crop water requirement with less than adequate well capacities.*

Root Zone: The horizontal distance of the soil profile occupied by the root system of the crop. The root zone is the portion of the soil profile that is generally considered to store water available for crop uptake. The depth of the root zone varies substantially during the growing season. It is a function of soil type, crop type, precipitation pattern, irrigation practices (application amount, frequency, irrigation method), soil structure (i.e., compaction), and other factors.

The *effective root zone* is defined as the soil profile in which about 80-90 percent of the total root density is located. For example, while maize can uptake soil water down to 6-8 ft in silt loam soils, the effective root zone of maize in silt loam soils is usually considered to be 4 ft. While soybean can uptake soil water down to 5-6 ft, the effective root zone for soybean in silt-loam soil is about 3 ft. Crops, in general, will have shallower a root zone in coarse-textured soils than in fine-textured soils. Crops will usually have a shallower root zone in wet conditions than in dry conditions.

Runoff: The portion of rain and/or irrigation water that falls on the field/ground surface that is discharged through stream channels. Surface runoff is defined as the water that moves off or leaves the field without infiltrating into the soil profile.

Run-on: Water that moves from one location in the field to another as a function of change in elevation and slope, and soil moisture gradient but does not leave the field. The amount of water that runs on within the field can cause nonuniform redistribution of water on topsoil. In the soil profile, that may result in differences in plant water and nutrient uptake, emergence, and crop growth and development as well as yield.

Saturation Point: The degree of soil wetness where all soil pores are filled with water; the wettest possible condition of a soil. It is also defined as the soil water content when all pores are filled with water. In natural conditions, the saturation point of any soil may not be reached due to presence of trapped air bubbles. Thus, the term "near-saturation" may be more descriptive. The saturation point can range from 10-15 percent vol for very coarse-textured soils to 55 percent vol for fine-textured soils. The amount of water at saturation point for various soil types is presented in *Figure 4*.

Table 5: Sensitivity of various field crops to water stress (FAO, 1989).

Low	*Low-Medium*	*Medium-High*	*High*
Cassava	Alfalfa	Beans (dry/edible)	Banana
Cotton	Citrus	Cabbage	Fresh/green vegetables
Millet	Grape	Maize	Paddy rice
Pigeon pea	Groundnuts	Onion	Potato
Sorghum	Soybean	Peas	Sugarcane
	Sugarbeet	Pepper	
	Sunflower	Tomato	
	Wheat	Watermelon	

Seepage: The water that drains below the irrigation canal, or subirrigation that depends on controlling the shallow water table (moving upwards) for irrigation by wetting the soil around the crop root zone.

Sensitivity to Water Stress: In general, crops grown for their fresh leaves and/or fruits are more sensitive to water stress than those grown for their dry grain or fruits. Major crops can be divided into four categories, as presented in *Table 5*, based on their sensitivity (in terms of yield production).

In general, the growing season for most crops can be divided into four major stages: early (initial) (from planting to 10 percent canopy cover); crop development stage (from 10 percent to 70 percent canopy cover); mid-season stage (flowering, grain setting/grain formation); and late-season stage (maturity, senescence, and harvest). In many cases, crops are most sensitive to water stress during the mid-season or reproductive stage and least sensitive during the late-season stage. Most crops are moderately sensitive to water stress during vegetative stages. However, the sensitivity to water stress can substantially change with the crop type. The most sensitive stages to water stress for different crops are presented in *Table 6*.

Table 6: Crop growth and development stages that are most sensitive to water stress (FAO, 1989).

Crop	*Most sensitive period*
Alfalfa (for forage production)	Immediately after cutting
Alfalfa (for seed production)	Flowering
Banana	Throughout the growing season
Beans (edible/dry)	Flowering and pod filling
Cabbage	Head enlargement and ripening
Citrus	Flowering and fruit setting, more than fruit enlargement
Cotton	Flowering and boll formation
Grape	Vegetative period and flowering, more than fruit filling
Groundnut	Flowering and pod setting
Maize	Flowering (tasseling) and grain filling
Olive	Just prior to flowering and yield formation
Onion (fresh)	Bulb enlargement
Onion (seed)	Flowering
Pea (fresh)	Flowering and yield formation
Pea (dry)	Ripening
Pepper	Throughout the growing season
Pineapple	Vegetative period
Potato	Stolonization and tuber initiation
Rice	Head development and flowering
Sorghum	Flowering and yield formation
Soybean	Flowering and yield formation
Sugarbeet	First four weeks after emergence
Sugarcane	Vegetative period (tillering and stem elongation)
Sunflower	Flowering, more than yield formation
Tobacco	Period of rapid growth
Tomato	Flowering, more than yield formation
Watermelon	Flowering and fruit filling
Wheat	Flowering, more than yield formation

Soil Aggregates: Soil particles that vary substantially in chemical and physical composition, and in size, shape, and orientation in their structural characteristics. The soil matrix also contains amorphous (unstructured) substances such as organic matter, which are attached (bounded) to the mineral grains and may bind them in congregations (assemblies) that are called *aggregates*. Soil aggregate is influenced by not only soil's chemical and physical properties, but also by environmental factors, residue management, irrigation method and management, and soil management as well as cropping systems cultivated.

Soil Matric Potential: One of the components of the total water potential that characterizes the tenacity with which water molecules are held by the soil matrix. Soil matric potential indicates the ability and the amount of energy that must be exerted by plants to extract water molecules from soil particles, or aggregates (*Figure 6*).

As the matric potential values increase (larger negative value), the availability of soil water to plants decreases and, thus, the plants need to exert more energy to be able to uptake water as soil water content decreases. Soil matric potential, rather than the soil water content, determines the availability of water to plants. Therefore, for studies involving water transport and storage in soils and soil-water-plant relationships, as well as scheduling irrigations based on the soil matric potential rather than water content, soil matric potential is often preferred (or should be preferred).

The relationship between soil water content and soil matric potential is described by *soil-water retention curve* (sometimes also called *soil moisture characteristics curve*). An example of a typical soil-water retention curve for a silty clay loam and a sandy loam soil is presented in *Figure 7*.

The silty clay loam soil has a particle size distribution of 10 percent sand, 34 percent clay, 53.5 percent silt, and 2.5 percent organic matter content; 37.7 percent vol field capacity; 19.3 percent vol wilting point; 55.5 percent vol saturation; 9.6 mm/hr (0.38 inch/hr) saturated hydraulic conductivity; and a bulk density of 1.18 gr/cm^3 (73.66 lb/ft^3).

The sandy loam soil has 65 percent sand, 10 percent clay, 23.5 percent silt, and 1.5 percent organic matter content; 21.9 percent vol field capacity; 9.6 percent vol wilting point; 43.8 percent saturation point; 38 mm/hr (1.5 inch/hr) saturated hydraulic conductivity; and 1.50 gr/cm^3 (93.64 lb/ft^3) of bulk density.

Since the availability of soil water to plants varies with soil textural properties, the amount of water available (held) in the soil at the same matric potential value varies with the soil type. In general, as the clay content increases, the amount of water retained at a given matric potential increases. For example, as presented in *Figure 7*, the soil water content at 100 kPa matric potential for the silty clay loam soil, which has 34 percent clay, is about 32 percent vol, whereas it is only about 18 percent vol for the sandy loam soil, which has only 10 percent clay content.

If the soil water content type sensor is used to measure soil water status, the amount of water held or depleted in the soil at any given time can be calculated easily. If the soil matric potential-based sensor is used, the soil matric potential needs to be converted to soil-water content, using the soil-water retention curve to calculate the amount of water available or depleted at any given time. The amount of soil water held or depleted at various soil matric potential values for various soil types was presented in *Table 4* earlier. Soil-water retention curves can be developed using pedotransfer functions for various soil textures (for example: Soil Water Characteristics/Hydraulic Properties Calculator developed by K.E. Saxton and W.J. Rawls, 2006).

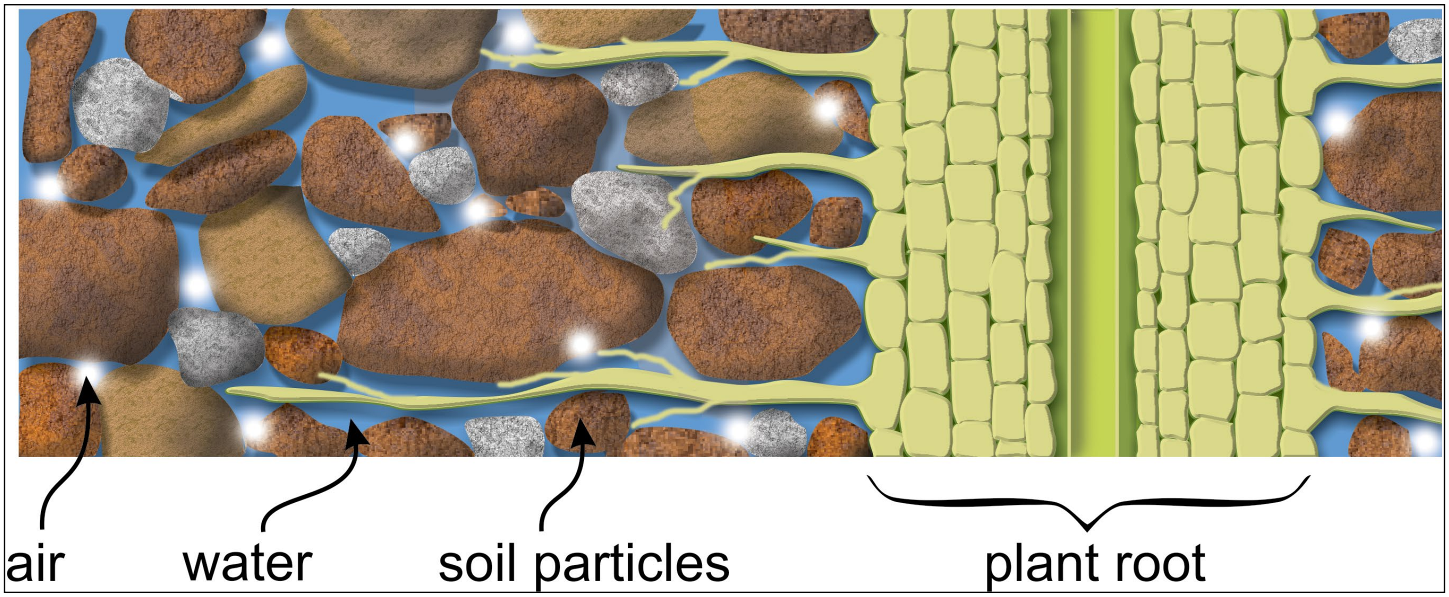

Figure 6: Soil structure components that influence soil matric potential value, in addition to soil water content.

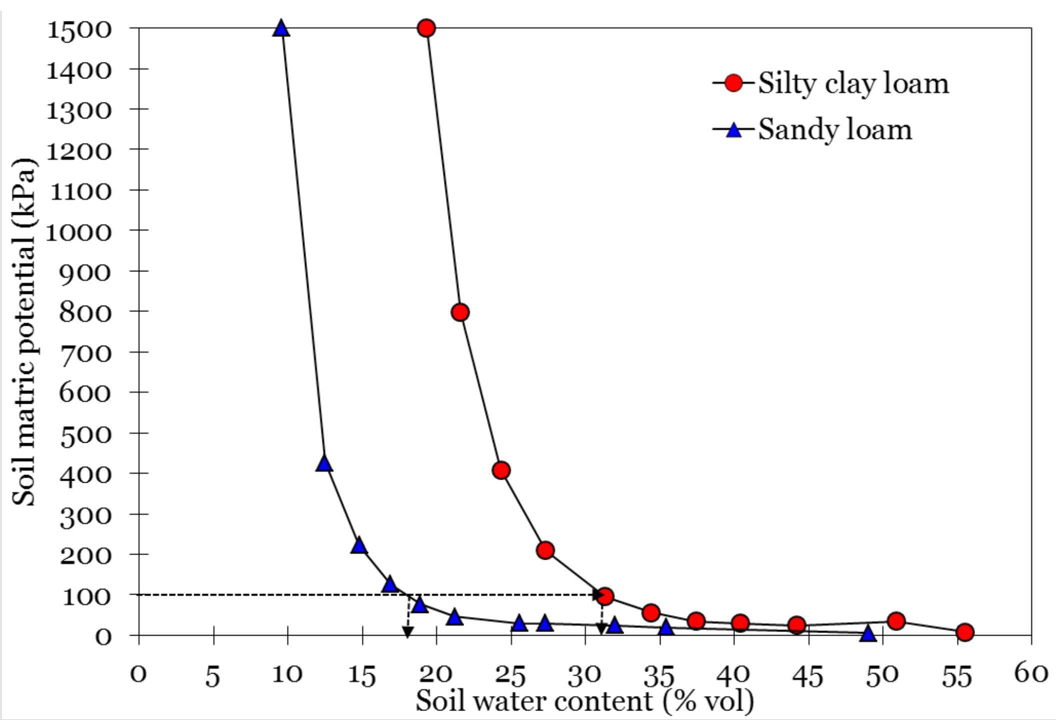

Figure 7: Example of soil-water retention curve for silty clay loam and sandy loam soils (example developed using Soil Water Characteristics/Hydraulic Properties Calculator developed by K.E. Saxton and W.J. Rawls, 2006).

Soil matric potential is a negative number. However, because it is implicit, sometimes, the negative sign is omitted or the term "tension" is used. In *Figure 7* and *Table 4*, the negative sign is omitted. Various units have been used to express soil water potential. It is usually given in units of pressure such as bars or atmosphere (1 bar ≈1 atm ≈14.5 psi), and in units of height (head) of an equivalent water column in centimeter (1 bar = 1022 cm H_2O @ sea level, 20°C) or equivalent mercury column in centimeters (1 bar = 75 cm H_g @ sea level, 45° latitude). The soil water potential can also be given in units of $erg\text{-}g^{-1}$ (1 bar = 1 x 10^6 $erg\text{-}g^{-1}$), or more conveniently, in $joule\text{-}kg^{-1}$ (1 bar = 100 $joule\text{-}kg^{-1}$). Commonly used subunits are megapascal (MPa), kilopascal (kPa), centibars (cb), and millibars (mb) (1 bar = 0.1 MPa = 100 kPa = 100 cb = 1000 mb).

Soil Porosity: An index of the relative soil pore space that indicates the amount of pore or open space between the soil particles. Coarse-textured soils (e.g., sandy) are more porosive then fine-textured soils (e.g., clay or silt loam). In most soils, the porosity ranges approximately from 30 to 60 percent of the total soil volume. *Fine-textured soils have more total pore space than coarse-textured soils. However, the individual pores sizes in fine-textured soil are much smaller than those in soils with a high sand content.* Therefore, clay soils (fine-textured) hold more water than coarse-textured soils, but because of the large surface area of the clay particles, much of this water is held strongly by the soil matrix, making it difficult for plants to extract the strongly-bounded water molecules.

On the other hand, coarse-textured soils (sandy soils) have relatively large particles that do not pack together tightly. Consequently, pore spaces are large, except when soils have recently been wetted and water occupies only small (capillary) pores, where it is held by absorption to the soil particles and air occupies the larger pores. Soils with a large proportion of large particles, such as sands, or with a compacted structure in which particles are close together have a low *total porosity.*

Medium-textured soils, with high organic matter content and little compaction, have a high total porosity due to the increase in capillary pores. Soil pores are categorized in two size classes: *macro* and *micro*. The larger *macropores* allow the rapid movement of air and percolating water, but they retain little water. In contrast, water is retained in *micropores*, but air and water movement is slow.

Sandy soils have low total porosity, but a large proportion of that porosity consists of macropores. Consequently, the movement of air and water is rapid. Quantification of soil porosity is relatively straightforward in coarse-textured soils, but very difficult in clayey soils because as the clay soil swells and shrinks as a function of changes in soil water status, the porosity value exhibits substantial variability (Hillel, 1998).

Soil Respiration: A measure of carbon dioxide produced in the soil due to decomposition of organic matter by the soil microbial community and respiration from plant roots. It is indicative of the aeration requirement of the soil. The soil respiration rate varies spatially and temporally, and is influenced by many factors such as soil temperature, soil water status, pH, organic matter content as well as its composition (i.e., fresh/new vs. decayed).

All these factors influence the temporal variability of respiration rates of different microorganisms and plant roots in the soil. During summer, soil respiration rates can be up to 10 times (or more) greater than those in winter.

Respiration rates are also influenced by the microorganism activities, which also have seasonality, because they are also influenced by soil temperature. Different plants modify the soil environment (mostly in rhizoshere – in the crop root zone) differently to increase plant nutrient availability and micorize associations and to provide favorable conditions for bacterial activity that decomposes organic matter into plant-available nutrients.

A difference in seasonality in respiration differs between cool season crops (wheat) vs. warm season crops (soybean). Soil respiration rates can be used in quantification of carbon sequestration by different soil management and cropping systems. The soil respiration rate is usually greater in cropped soil than in fallow soil (Hagan et al., 1967; Stewart and Nielsen, 1990; Hillel, 1998).

Soil Sealing (Crusting): When rain drops and/or sprinkler irrigation drops reach the soil surface, the impact force that creates kinetic energy can break and obliterate (disturb or destroy) established soil aggregates at the soil surface. This causes the surface to seal, which decreases infiltration rate and causes surface runoff.

During a surface wetting event, soil aggregates may satiate and collapse, forming a layer of dispersed (detached or disturbed) mud. The thickness of this collapsed mud can be up to 5 cm or greater. This process clogs the macropores of the topsoil surface and impedes the infiltration of rain and/or irrigation water. The surface sealing can also impede exchange of gasses between the soil and the surrounding atmosphere.

When the surface sealing dries out and shrinks, it becomes a hard crust and may crack. This may damage the newly emerged plants. Surface seal depends on the rainfall or irrigation rate, initial soil water status of surface soil, soil type, and other factors. Soil sealing can occur almost in every soil type.

Table 7: Diameter, volume, and surface area of various soil particles (textures) (from Baver, 1966).

Diameter of sphere	Textural name	Volume per particle ($\frac{1}{6}\pi D^3$)	Number of particles in $\frac{\pi}{6}$ cc.	Total surface $\pi D^2 \times$ number of particles
1 cm.	Gravel	$\frac{1}{6}\pi(1)^3$	1	3.14 sq. cm. = 0.49 sq. in.
0.1 cm. (1 mm.)	Coarse sand	$\frac{1}{6}\pi\left(\frac{1}{10}\right)^3$	1×10^3	31.42 sq. cm. = 4.87 sq. in.
0.05 cm. (0.5 mm. or 500 μ)	Medium sand	$\frac{1}{6}\pi\left(\frac{5}{100}\right)^3$	8×10^3	62.83 sq. cm. = 9.74 sq. in.
0.01 cm. (0.1 mm. or 100 μ)	Very fine sand	$\frac{1}{6}\pi\left(\frac{1}{100}\right)^3$	1×10^6	314.16 sq. cm. = 48.67 sq. in.
0.005 cm. (0.05 mm. or 50 μ)	Coarse silt	$\frac{1}{6}\pi\left(\frac{5}{1000}\right)^3$	8×10^6	628.32 sq. cm. = 97.34 sq. in.
0.002 cm. (0.02 mm. or 20 μ)	Silt	$\frac{1}{6}\pi\left(\frac{2}{1000}\right)^3$	125×10^6	1,570.8 sq. cm. = 1.69 sq. ft.
0.0005 cm. (0.005 mm. or 5 μ)	Fine silt	$\frac{1}{6}\pi\left(\frac{5}{10,000}\right)^3$	8×10^9	6,283.2 sq. cm. = 6.76 sq. ft.
0.0002 cm. (0.002 mm. or 2 μ)	Clay	$\frac{1}{6}\pi\left(\frac{2}{10,000}\right)^3$	125×10^9	15,708 sq. cm. = 16. 9 sq. ft.
0.0001 cm. (0.001 mm. or 1 μ)	Clay	$\frac{1}{6}\pi\left(\frac{1}{10,000}\right)^3$	1×10^{12}	31,416 sq. cm. = 33.8 sq. ft.
0.00005 cm. (0.0005 mm. or 500 mμ)	Clay	$\frac{1}{6}\pi\left(\frac{5}{100,000}\right)^3$	8×10^{12}	62,832 sq. cm. = 67.6 sq. ft.
0.00002 cm. (0.0002 mm. or 200 mμ)	Colloidal clay	$\frac{1}{6}\pi\left(\frac{2}{100,000}\right)^3$	125×10^{12}	157,080 sq. cm. = 169 sq. ft.
0.00001 cm. (0.0001 mm. or 100 mμ)	Colloidal clay	$\frac{1}{6}\pi\left(\frac{1}{100,000}\right)^3$	1×10^{15}	314,160 sq. cm. = 338 sq. ft.
0.000005 cm. (0.00005 mm. or 50 mμ)	Colloidal clay	$\frac{1}{6}\pi\left(\frac{5}{1,000,000}\right)^3$	8×10^{15}	628,320 sq. cm. = 676 sq. ft.

Soil Structure: How the individual soil particles of different sizes combine into aggregates. Soil structure is particularly important in fine-textured soils where aeration can be a problem. Large pores around aggregates provide good water movement and aeration despite relatively small pores around individual particles (Hillel, 1998).

Soil Texture: The relative proportions of sand, silt, and clay in a soil. Soil texture is associated with the particle size distribution (characteristics). Clay is the smallest particle size, and clay soils tend to hold water and nutrients well and drain poorly.

Conversely, soils containing a large proportion of sand (the largest particle size) tend to drain well and do not hold water and nutrients well. The area of solid (soil) surface accessible to water ranges from less than 1,000 cm^2/gr (70,308 $inch^2$/lb) of soil for coarse sand to more than 1,000,000 cm^2/gr (70,308,000 $inch^2$/lb) of soil for clay soils. Diameter, volume, and surface area of various soil particles (textures) are presented in *Table 7*.

Soil Water Content: The volume of water present in a unit volume of soil. It is the percentage of water held by the soil and can be expressed in terms of either percentage by dry weight or volume basis. The water content of a soil sample on a dry weight basis (θ_{dw}), which is also called gravimetric water content, is defined as the grams of water per gram of oven-dry soil. It is usually expressed as a percent and can be calculated as:

$$\theta_{dw} = [(WW - DW) / (DW)] \times 100$$

where,
WW = wet weight of the soil sample (gr)
DW = dry weight of the soil sample (gr)

It is often convenient to express soil water content on a volume basis (θ_v), i.e., the ratio of the soil water volume to the bulk soil volume. It is a more suitable expression than the water content expressed on a dry weight basis for irrigation and drainage calculations and for theoretical considerations of water retention and flow in a porous medium (soil). This is because additions to, and losses of, water from soil are often measured in inches or millimeters, which on an area basis become volume. The water content on volume basis can be calculated as:

$$\theta_v = \theta_{dw} \times (\rho_b / \gamma_w)$$

where,
ρ_b = bulk density of soil (g/cm^3 or Mg/m^3)
γ_w = density of water (usually 1.0 g/cm^3)

After water content is determined on a volumetric basis, it can be expressed in convenient units for irrigators such as inches per foot or centimeters per meter of soil depth. For example, a soil with a water content of 10 percent by volume contains (10 percent) x (12 in/ft) = 1.2 inches of water per foot of soil depth. The accuracy of the volume-basis water content calculations depends upon the accuracy of the bulk density used as well as the accuracy of the dry weight water content value.

The soil bulk density is defined as the oven dry (at 105°C until the soil sample reaches a constant weight) mass of soil in a given volume. It can be measured by drying and weighing a known volume of soil. The mass of dry soil divided by the total volume (solids plus voids) will give the bulk density value.

In practice, usually 100 cm^3 (6.1 $inch^3$) in volume standard soil sampling cylinders are used to take undisturbed soil samples to determine soil bulk density. For non-swelling soils (e.g., sand) the bulk density of soil does not change with water content, and the calculation of ρ_b is relatively easy. Considering the heterogeneity of soil, enough soil samples should be taken and then averaged to determine both bulk density and soil water content in a given field to increase the accuracy of measurements. Many factors influence spatial and temporal distribution of soil water content, including wetting frequency, uniformity of irrigation and rainfall, uniformity of crop emergence, soil textural properties, evaporation, and transpiration rate, etc. Soil compaction can also influence soil water status by increasing soil bulk density and consequently reducing the porosity. Soil water status usually decreases as compaction increases, reducing the infiltration rate and the amount of water available to the soil.

Soil Water Deficit: The amount of water that is used or depleted by crops via water uptake and transpiration and/or evaporated from soil between two irrigation events that needs to be replenished with the next irrigation to keep pace with the crop water demand. In general terms, soil water deficit in relation to irrigation represents the amount of water between field capacity and the current (just before the next irrigation) soil water status.

While replenishing soil water status to the field capacity with each irrigation is commonly practiced, in humid and subhumid regions and regions with soils that have relatively good soil water holding capacity (e.g., silt loam), soil water can be replenished to about 80-90 percent of the field capacity to reserve some soil water storage capacity for any potential precipitation. Reserving storage capacity for potential rainfall can also aid in reducing surface runoff from heavy rainfall by allowing some of the rainwater to infiltrate into the soil.

Subirrigation: The process of regulating the groundwater table by artificially adding water to the field underground. When water is being added to the root zone, a balance between water and air (oxygen) is maintained for optimum crop growth and development. In most cases, water is added to the underground soil profile via drain tiles or perforated pipes, and the water is moved into or from the tiles or perforated pipes due to the difference in elevation gradient between the groundwater table and the tile or perforated pipe (Criddle and Kalisvaart, 1967).

In some conditions, due to natural and topographical conditions, the depth to the groundwater table can be small enough to be managed in a way to wet the crop root zone for irrigation purposes. This can be done by raising the water table close to the surface to wet the soil directly under the surface, which is known as subirrigation. In many cases, tile drains are used to control water in subirrigation. Thus, subirrigation consists of manipulation or control of the groundwater level by means of change in elevation of the drain outlet using ditches or buried perforated pipe systems and a sump (submersible) pump to move the water close to the soil surface or crop root zone and drain it from the crop root zone. An impermeable subsoil at a depth of about 5-6 ft or more, a highly permeable loam, sand, or sandy loam surface soil, and a relatively uniform field slope are favorable conditions for subirrigation.

In summertime, the water table can be raised to irrigate the crops (*subirrigation mode, Figure 8a*); and the control structure can be adjusted in the fall and spring for drainage to remove excess water from the field so that field operations can proceed (*drainage mode, Figure 8b*). When precipitation and/or upward water movement exceeds the rate of evapotranspiration, the water table will be higher than the tile or perforated pipelines; and in this case the tiles/perforated pipes will serve as the drainage system.

In most cases, the subirrigation system only works when drainage is needed in the field. The elevation difference of the water levels in the subirrigated field is influenced by the quantity of water that is discharged or supplied to the tiles; the permeability of the soil profile above the groundwater table; the thickness of the permeable layer; and spacing between the tiles. Even though the spacing between the tiles can be adjusted, based on the slope and soil physical characteristics as well as the amount of water that can be discharged from or supplied to the system, in general, tile spacing would have minimal influence on the evapotranspiration rate, seepage, and the thickness of the soil that conducts the water, and the difference in water level would be nearly proportional to the square of the distance between the tiles (Criddle and Kalisvaart, 1967).

Subirrigation can be divided into three categories: (i) subirrigation to saturation, (ii) controlled injection subirrigation, and (iii) constant water level subirrigation. In the *subirrigation to saturation* method, water is injected into the tile in the bottom of the bench until the soil surface is completely flooded and reaches near saturation. Then the outlet plug is removed and the excess water is drained. This method can result in significant water losses and can leach salts and other chemicals, including fertilizers, and is a very inefficient way of irrigating the field.

With the *controlled injection subirrigation* method, when the soil matric potential reaches a desired level, depending on the soil textural properties, a predetermined amount of water is delivered into the subirrigation tile to wet the soil by capillary rising in about two to three hours. One of the main difficulties with this approach is uneven distribution of nutrients from the lower to the upper levels of the field, as is the case with most surface irrigation methods. Salt accumulation at the soil surface can also be an issue, which requires routine monitoring of the surface soil salt concentration.

This kind of subirrigation, which is also practiced extensively for potted plants and large scale nursery operations, is sometimes referred to as bottom-up irrigation. The constant water level subirrigation method is mainly used in potted plant production and maintains a constant water level in the topsoil (e.g., 1 inch below the soil surface) by means of a float valve. Salt accumulation in the topsoil can be a significant issue that requires periodic leaching of salts using sprinkler irrigation (Criddle and Kalisvaart, 1967).

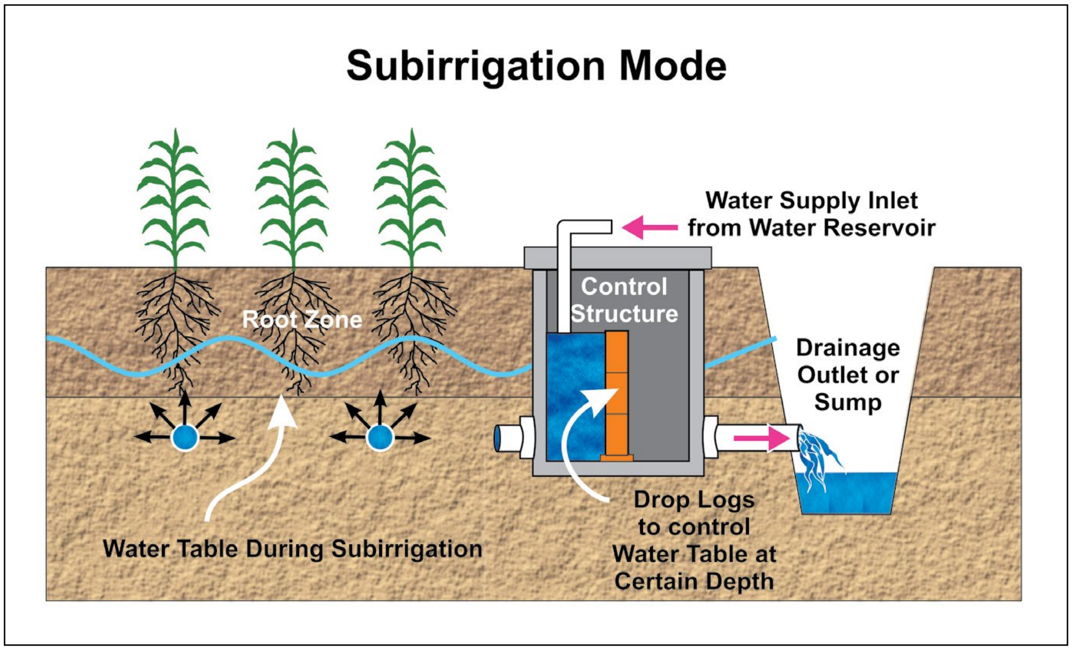

Figure 8a: Basic components of subirrigation system that is operated in a subirrigation mode. (Adopted from Brown et al., 1997).

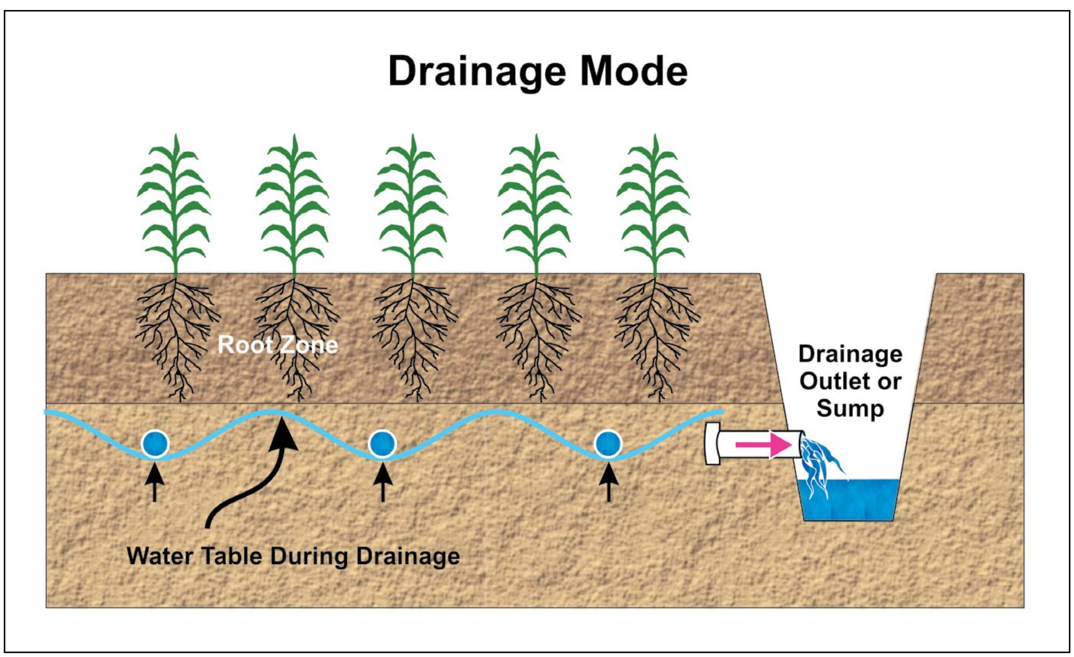

Figure 8b: Basic components of subirrigation system that is operated in a drainage mode. (Adopted from Brown et al., 1997).

Practicing subirrigation in soils with silt or clay layers (even with good permeability) can present challenges. These soils generally have a slow capillary rise characteristic and they often lose their permeability under subirrigation. Thus, subirrigation in such soils may be suitable in the initial stages, but when saturated conditions are attained, they often become less permeable or even impermeable and lose their suitability for subirrigation practices.

In some cases, depending on the salinity levels of water and soil, subirrigated lands can develop salinity and alkali conditions by upward capillary water movement from the shallow water table. When the water evaporates from the topsoil, the salt concentration can build up, which may result in less productive soil conditions. If the salt buildup cannot be removed via irrigation, including the leaching requirement (*leaching requirement is an estimate of amount of water leaching required to maintain soil water salinity within acceptable/tolerable levels to prevent or minimize yield reduction due to salinity*), subirrigation may need to be discontinued and other irrigation methods (e.g., sprinkler) may need to be practiced to leach the salt (Criddle and Kalisvaart, 1967). *Subirrigation*, in some cases, is also referred to as *subsurface irrigation* or *reverse drainage irrigation* and is also confused with *subsurface drip irrigation*, but subirrigation and subsurface drip irrigation are two significantly different irrigation methods and practices.

The feasibility of using a subirrigation system in Nebraska ranges from extremely limited to nonexistent because the water table is well below the crop root zone for the subirrigation to work. California (Sacramento-San Joaquin Delta) and central-south central Florida have large areas that are successfully irrigated by subirrigation. Favorable soil physical characteristics, which allow free lateral movement of water, *rapid capillary movement* in the crop root zone, and *slow downward movement in the subsoil*, are essential for successful implementation of subirrigation. Thus, the subirrigation method is not suitable in all soil types (Criddle and Kalisvaart, 1967).

Surface Irrigation: Surface irrigation, in general, can be defined as irrigating crops using canals, ditches, and within-field structures such as furrows, borders, and basins that deliver water to the fields/crops using only gravitational force. Thus, the system flow as well as the performance relies heavily on the slope and other soil and field/land characteristics such as soil textural characteristics (particle size distribution; percent sand, silt, clay), infiltration rate, surface roughness, slope, and the furrow/basin/border inflow rate (gpm per foot of furrow, basin, or border width). Surface irrigation methods include furrow irrigation, border-strip or flood irrigation, basin irrigation, and to some extent subirrigation. Surface irrigation channels vary greatly in shape, size, and hydraulic characteristics. Since infiltration of water into the soil occurs, the stream size inside the furrow or border decreases along this furrow channel.

During a surface irrigation event, the top end of the field would have a much wetter, deeper soil profile, due to its being subject to the water flow for the longest time, and the soil profile at the bottom end of the field is usually wetted the least, causing nonuniform water application along the furrow/border. The bottom end of the furrows can be blocked to enhance water infiltration. The water reuse pits can be used to collect water from surface irrigation runoff. The water can be pumped back to the top end of the field for reuse to enhance the overall efficiency of the surface irrigation systems.

Globally, surface irrigation is, by far, the most commonly practiced irrigation method. It can be used on essentially all irrigable soils except sandy soils and most crops. The flow rate (system capacity) of most surface irrigation systems is large enough that the entire field can be irrigated in a shorter period of time, compared to the other pressurized irrigation methods. This provides flexibility in terms of delivering water to the field quickly during extreme dry and windy conditions when the crop water demand is high. Surface irrigation methods are the least expensive irrigation methods due to low power requirements, but their labor requirements can be a very important factor in terms their applicability and economical comparisons in relation to other irrigation methods (Hanson and Schwankl, 1995).

Furrow irrigation, which is the most commonly used surface irrigation, can be classified as graded, level, or contour furrows based on the orientation of the furrows in relation to the field slope. Graded furrows follow the direction of the field slope, while a level furrow usually indicates that the field does not have much slope. Contour furrows follow the topography of the field. Graded furrows may follow a slope in one direction, while a second, cross-slope, running perpendicular to the first, delivers water by gravity flow along a head ditch from which the furrows originate. In most cases, siphon tubes or gated pipes are used to deliver water to the furrows. (Hanson and Schwankl, 1995).

Surge Irrigation: Water is applied/advanced in the furrow or across the field in the on- and off- cycles to have some degree of control in water infiltration and to aid in establishing a balance between infiltration and water advancement along the furrow. In surface irrigation methods (e.g., furrow), if the water flows over the surface too fast, an insufficient amount of water will infiltrate (percolate) into the soil profile. If the water flows too slowly, waste can result due to the large amount of deep percolation below the crop root zone. It is an important, and difficult, process to have the optimum flow rate and proper advancement of water in the furrows to enable optimum infiltration.. With surge irrigation, the water flows down the field for a certain distance (e.g., 100-150 ft), and then the flow is stopped until the water in the furrow has receded.

The next water surge will wet the previously wetted distance (and water in the previously wetted distance will advance faster) again as well as the soil after the previously wetted area (new dry area beyond the first 100-150 ft distance). The water flow is stopped again while water recedes again, and the third surge is started.

This process is continued until the water reaches the bottom end of the field. During the time when the water flow is cut off to wait for the water to recede, water can be diverted to other parts of the field to save irrigation time. The time it takes for water to recede, and the total time it takes for water to reach the end of the field, as well as the amount of water infiltrated, depend on many soil physical characteristics, slope, residue cover, field length, surface roughness, flow rate of surged water, soil infiltration rate, initial soil moisture content, and other factors (Hanson et al., 1998).

In surge irrigation, the cycling of water in the advance phase results in reduced infiltration of water and water moves faster down the furrow, compared with the traditional continuous furrow irrigation with the same flow rate. Thus, in surge irrigation, less water is needed to irrigate the same field size, which may result in increasing overall irrigation efficiency. It is important to determine the cycle length, cycle ratio, and the number of surges needed experimentally for local soil types as well as soil and crop management conditions. Surge irrigation, in certain cases, is also referred to as *ebb-flow* or *ebb-and-flow* irrigation (Hanson et al., 1998).

Tailwater: Water that leaves the field during and/or after an irrigation event, usually associated with surface irrigation methods, especially furrow irrigation. Tailwater, in many cases, is collected in the reuse pits at the lower end of the field and pumped back to the top end of the field where it is delivered again to the field for irrigation. Gated pipes, ditches, or canals are used, which results in increased overall efficiency of the surface irrigation methods. In most cases, the amount of tailwater is expressed as a water depth or volume. When it is expressed as depth (i.e., inch), the volume of the tailwater is considered to be uniformly distributed over the irrigated field area.

Transpiration: The water loss through leaf stomata in the form of very small water vapor particles into the surrounding atmosphere. The transpiration rate of any plant species depends on many factors, which can be categorized in three groups: plant factors, soil-water factors, and atmospheric factors. During the transpiration process, water is being extracted from the soil particles through the root system, carried out through the plant, and released into the atmosphere through small pores on the top and bottom of the leaf surface (stomata).

Every opening of stomata also allows influx of atmospheric CO_2 into the leaf tissue and its fixation into the carbon molecules (hexose) through the process of photosynthesis. In terms of atmospheric factors, the transpiration rate is influenced by factors similar to the evaporation process (solar radiation, air temperature, relative humidity, vapor pressure deficit, and wind speed). Unlike evaporation, transpiration is perhaps the most beneficially used amount of water in agricultural-crop production settings, as it sets the biomass production and determines/enables the quantity of yield and water productivity.

Water Conveyance Efficiency: The ratio between the irrigation water that reaches a farm or field to that diverted from the water source. Irrigation water is normally conveyed from a water source to the farm or field through natural drainage ways, constructed earthen or lined canals, or pipelines. Many conveyance systems have transmission losses, meaning that water delivered to the farm or field is usually less than the water diverted from its source. Water losses in the conveyance system include canal seepage, canal spills (operational or accidental), evaporation losses from canals, and leaks in pipelines. The water conveyance efficiency is expressed as:

$$E_c = (V_f / V_t) \times 100$$

E_c = water conveyance efficiency (%)
V_f = volume of irrigation water that reaches the farm or field (acre-inch)
V_t = volume of irrigation water diverted from the water source (acre-inch)

The water conveyance efficiency can also be applied to evaluate individual segments of canals or pipelines. Typically, conveyance losses are much lower for pipelines due to reduced evaporation and seepage losses. In Nebraska, irrigation water is frequently pumped from wells located in the field and carried in pipelines. Water delivery through open canals is also common, especially in the central and western parts of the state. Since there is minimal water loss in closed/pressurized conveyance systems, the conveyance efficiency can be as high as 100 percent.

Water Holding Capacity (Available Water Capacity): The amount of water held in the soil profile between field capacity and the permanent wilting point (*Figure 3*). The available water holding capacity (WHC) values varies substantially between the soils as a function of soil textural characteristics. Some of the very productive soils in the Midwestern and Western United States have WHC values ranging from 0.75 to 3 inch/ft. The WHC values for various soil types common in Nebraska, typical agricultural soils in Midwestern United States, are provided in *Table 4*.

The total available water in the crop root zone can be calculated by multiplying the root zone depth by the water holding capacity per soil layer (ft). The values are summed for the root zone, which varies by crop type and other factors. Since soil profile physical properties can vary spatially, each soil layer can have different WHC values. Thus, in irrigation management, especially in precision and/or variable rate irrigation and fertigation practices, spatial variability of different soil layers should be taken into account when determining irrigation demands for a specific part of the field.

References

ASAE, 2003. Design and installation of microirrigation systems. EP405.1 February 2003. pp. 900-905.

Baver, L.D. 1948. Soil Physics. 2nd Edition. John Villey & Sons, Inc. New York. 398 pp.

Boman, B. 1989. Distribution patterns of microirrigation spinner and spray emitters. *Applied Engineering in Agriculture.* 5(1): 50-56.

Brown, L.C., A. Ward, and N.R. Fausey. 1997. Agricultural Water Table Management Systems. Ohio State University Extension Fact Sheet. AEX 321-97. Columbus, Ohio.

Center Pivot Irrigation Management Handbook. 2011. University of Nebraska–Lincoln Extension publication.

Criddle, W.D., and C. Kalisvaart. 1967. Subirrigation Systems. *In:* Irrigation of Agricultural Lands. (Hagan, R.M., H.R. Haise, and T.W. Edminster (Eds.). Agronomy Monograph No. 11. Am. Soc. Agron., Publisher. Madison, WI. 1180 pp.

FAO. 1978. Effective Rainfall in Agriculture. N.G. Dastane (Ed.). FAO Irrigation and Drainage Paper No. 25. Rome, Italy.

FAO Training Manual No. 4. 1989. Irrigation Water Management: Irrigation Scheduling. Water Resources, Development and Management Service Land and Water Development Division, FAO. C. Brouwer, K. Prins, and M. Heibloem (Eds.). FAO Land and Water Development Division. Rome, Italy. pp. 66.

FAO, 1992. The Use of Saline Waters for Crop Production. FAO Irrigation and Drainage Paper No. 48. J. D. Rhoades, A. Kandiah, and A.M. Mashali (Eds.). pp. 133. Rome, Italy.

FAO Water Reports. 2002. Deficit Irrigation Practices. FAO Technical Report, No. 22. pp. 103. Rome, Italy.

FAO. 2010. Food and Agricultural Commodities Production. Food and Agriculture Organization of the United Nations (FAO). (http://faostat.fao.org/site/339/default.aspx).

Free, G. R., G.M. Browning, and G.W. Musgrave. 1940. Relative infiltration and related physical characteristics of certain soils. USDA Tech. Bull. 729. Washington, D.C.

Hagan, R.M., H.R. Haise, and T.W. Edminster (Eds.). 1967. Irrigation of Agricultural Lands. R.C. Dinauer (Managing Editor). Agronomy Monograph No. 11. Am. Soc. Agron., Publisher. Madison, WI. 1180 pp.

Hammitt, W.E., and D.N. Cole. 1987. Wildland Recreation: Ecology and Management. Chapter 2: Soils. New York, NY, John Wiley.

Hanson, B.R. and L.J. Schwankl. 1995. Surface Irrigation. University of California-Davis, Division of Agricultural and Natural Resources Publication 3375. 105 pp.

Hanson, B., L. Schwankl, W. Bendixen, and K. Schulbach. 1998. Surge Irrigation. University of California-Davis, Division of Agriculture and Natural Resources Publication No. 3380. Davis, CA. 48 pp.

Hillel, D. 1998. Environmental Soil Physics: Fundamentals, Applications, and Environmental Considerations. Academic Press, Oval Road, London, UK. 775 pp.

Irmak, S., J.O. Payero, B. van DeWalle, J.M. Rees, and G.L. Zoubek. 2014. Principles and operational characteristics of Watermark granular matrix sensor to measure soil water status and its practical applications for irrigation management in various soil textures. University of Nebraska–Lincoln Extension Circular EC783.

Israelsen, O.W., and V.E. Hansen. 1962. Irrigation Principles and Practices. 3rd Edition. John Villey and Sons, Inc., New York. 447 pp.

Izuno, F.T., and D.Z. Haman. 1995. Basic Irrigation Terminology. Fact Sheet AE-66, University of Florida-Institute of Food and Agricultural Sciences. Gainesville, FL.

Saxton, K.E., and W.J. Rawls. 2006. Soil Water Characteristics. Hydraulic Properties Calculator. Ver. 6.02.74. USDA Agricultural Research Service and Washington State University, Pullman, WA.

Saxton, K.E., W.J. Rawls, J.S. Romberger, and R.I. Papendick. 1986. Estimating generalized soil-water characteristics from texture. *Soil Sci. Soc. Am. J.* 50(4): 1031-1036.

Saxton, K.E. and W.J. Rawls. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Sci. Soc. Am. J.* 70(5): 1569-1578.

Stewart, B.A., and D. R. Nielsen (Eds.). 1990. Irrigation of Agricultural Crops. Agronomy Monograph No. 30. Madison, WI. American Society of Agronomy, Crop Sciences Society of America and the Soil Science Society of America (Publisher). 1246 pp.

Zazueta, F.S., A.G. Smajstrla, and D.S. Harrison. 1984. Glossary of Trickle Irrigation Terms. University of Florida/Institute of Food and Agricultural Sciences. Gainesville, FL. Agricultural Engineering Fact Sheet AE-45.

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