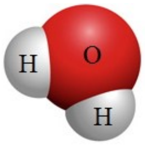
Technical Note 7. Ag Water Literacy III



7.7 Classifying Soil Water

In Technical Note 7 Part II soil water was described two ways namely, *water content* and *water potential*. We brandished jargon like *saturation*, *field capacity*, *permanent wilting point*, and *plant available water* without defining, exactly, what these terms mean. We also noted that water content and water potential measured different things but could be joined as relatable quantities. In Part III, we introduce the soil water characteristic, and a classification scheme based on how much water is left in the soil as water potential changes.

A typical agricultural soil is comprised of about equal portions air and mineral particles, a 50/50 mix, if you will. The mineral portion can be divided into three size-based particle classes: sand, silt, and clay. The proportion of the different particle size classes gives the soil its characteristic texture or "feel'. The pore spaces between particles may be classified as large ('macropores'), medium ('mesopores'), small ('micropores') according to subjective criteria but in all cases their fractional values add up to the total pore volume, or total porosity, of the soil. The soil's total porosity is also its *potential water reserve* because water can only occupy the space between solid particles. Soil water-porosity relationships are described in Technical Note 2, Section 2.3, and the classification of pore sizes in Section 7.4 of Technical Note 7 Part II. We encourage the reader to review that information as background to Part III.

Now, if the soil were initially dry, and we added water to it, the water would be distributed through the micropore fraction first because the smallest pore diameters exhibit lower matric potential or "pull" compared to larger pores. If we continued adding water, the mesopores would fill up next, followed by the macropores. This can't go on indefinitely because at some point, all of the pore space will be filled with water. The point where all the soil's pore space is occupied by water is called the ***saturation point***.[1] At the saturation point, capillary menisci are all flat and matric potential zero (**Figure 7.7.1A**).

Assuming free drainage, air will enter the saturated soil because the air pressure at sea level (1 atm) is higher than the water potential at the surface of the flat menisci (zero) thus air will exert a downward force pushing gravitational water through until the remaining is held by capillary forces. The rate at which gravitational water passes through is roughly proportional to the square of the pore diameter, i.e., water will move at least 100 times faster through a coarse sand than a loam soil. The point at which drainage stops (or becomes negligible) is called ***field capacity*** or the *upper limit* of water retention. The upper limit occurs at a matric potential between –5kPa and –30 kPa according to soil particle size distribution and minerology. Field capacity is an important hydraulic parameter because it represents the soil water content at the point where the forces of gravity and capillary tension (matric potential) are roughly in balance (**Figure 7.7.1C**). Field capacity also represents the soil's available water holding capacity, i.e., the fraction of total porosity holding water against the pull of gravity. In typical agricultural soils, water at field capacity occupies from 12% to 35% of the total porosity.

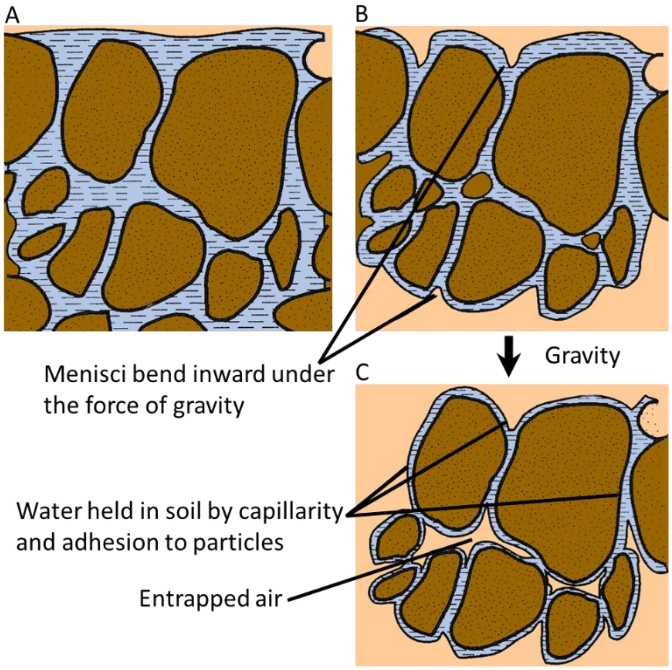


Figure 7.7.1 Three stages of water retention in the soil explained by gravitational and matric potential forces. At saturation (**A**), menisci are flat and the matric potential zero. As drainage begins (**B**), gravity bends the menisci inward (**B**) against the forces of surface tension and adhesion. Finally, the menisci are all bent (**C**), and water is held only in small pores by the force of adhesion to particle surfaces, i.e., capillarity.

Field capacity is temporary state that is short lived. Evaporation of water from the soil surface and transpiration from the plant canopy soon depletes the soil water content. When depletion reaches a critical point, roots can no longer oppose the matric forces of water molecules located very close to, or adsorbed on, soil particle surfaces. This critical point, which approximates a matric potential of -1,500 kPa, is the lower limit of ***plant available water*** exhibited by the forces of capillarity in **Figure 7.7.1**. At this critical point, the soil water content is so low that plants cannot recover from wilting even with irrigation. This is called the ***permanent wilting point***. Below this point, water is adsorbed to soil particle surfaces with such force it cannot be removed by

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[1] Soil can reach the saturation point with less than all the pore space occupied by water because of air entrapment. Some investigators think it's more accurate to speak of 'effective' saturation or 'satiation' when water intake ceases rather than true 'saturation'.

evaporation to the atmosphere. The fraction of soil water in equilibrium with atmospheric moisture content is called ***hygroscopic water*** associated with air-dried soil.

The difference between the amount of water held at field capacity and the permanent wilting point is called ***available water capacity*** *(AWC):*

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

where θ_{FC} and θ_{PWP} are the fractional volumes of water at field capacity and the permanent wilting points, respectively.

Available water capacity is, by definition, the amount of water that would be available to plants *if the soil were at field capacity*. Typical values are expressed as cm^3/cm^3, which is equivalent to depth of water per unit depth of soil (see TN Part II section 7.4). Of course, not all the water held at field capacity is equally available to plants. As depicted in **Figure 7.7.2**, the amount of plant available water decreases with matric potential. Water becomes progressively more difficult for plants to extract below -100 kPa, a tension head roughly corresponding to the boundary between soil structural porosity and inter-particle (matrix) porosity. A general rule of thumb is that about 50% of the water held in the soil at field capacity is ***readily available water*** or *RAW*. The rest is, technically, plant available water, but extracting it puts stress on the plant as it adjusts physiologically against the pull of lower matric potentials.

Plant available water content varies substantially with soil type. **Table 7.7.1** provides typical values for volumetric water content (VMC) for various soil textural classes at field capacity and the permanent wilting point including their available water capacity.

Table 7.7.1 Typical values of volumetric water parameters for various soil textures*. From Hignett and Evett 2008 and others.

Soil texture	Field capacity	Permanent wilting point	Available water
	water content, cm^3/cm^3		
Coarse sand	0.06	0.02	0.04
Fine sand	0.10	0.04	0.06
Loamy sand	0.14	0.06	0.08
Sandy loam	0.20	0.08	0.12
Loam	0.25	0.10	0.15
Sandy clay loam	0.28	0.13	0.15
Silt loam	0.30	0.13	0.17
Silty clay loam	0.38	0.22	0.16
Clay loam	0.40	0.25	0.15
Silty clay	0.40	0.27	0.13
Clay	0.40	0.28	0.12

*Values are representative of each textural class. Field samples may exhibit considerable variation depending on particle size distribution and minerology factors.

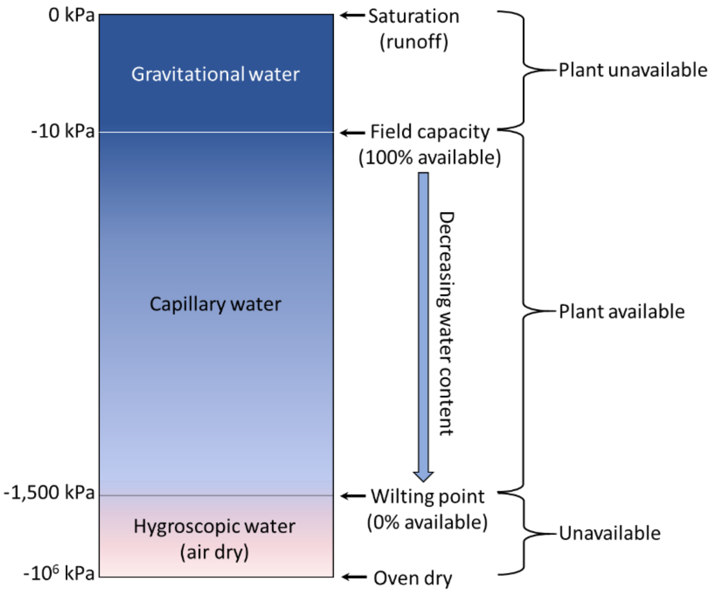


Figure 7.7.2 Block diagram illustrating the relationship between matric potential (MP, kPa) and the classification of soil water. *Adapted from McCarty et al. 2008 and Gardiner and Miller 2008.*

It can be noticed that soils with a high percentage of silt also have the highest available water capacity while sandy soils have the lowest. Clays are intermediate between sandy and silty soils. The reason for this has to do with the nature of sand, silt, and clay particles and the distribution of pore sizes in each mineral class. Sand and silt particles have no chemical bindings to water molecules whereas negatively charged clay particle attract and hold water (recall that water is a polar molecule). The arrangement and packing of silt (0.002 – 05 mm diameter) and clay (<0.002 mm diameter) particles creates a larger share of micropores compared to macropores. Consequently, soils with a higher percentage of silt particles tend to have a higher available water capacity, approaching 20 cm^3/cm^3 by volume or 20 cm H_2O/m soil (TN 7 Part II Sec. 7.4). Whereas, clay soils have the highest water retention capacity, but a larger percentage of that water is unavailable to plants due to higher matric tension in the micropore fraction and the adsorption of water by clay particles.

In general, plant available water content between 12% and 25% by volume is a favorable range with an ideal target of 18% (18 cm H_2O/m soil). Note that organic matter is a heterogenous class of particles that are also highly absorbent. Even the small quantities (~1% to 4%) normally found in mineral soils can impart agronomically important (or adverse engineering) water retention properties.

The concept of available water capacity is firmly entrenched in the agronomic sciences despite some ambiguity regarding the precise limits of field capacity. In sandy soils, matric potentials between -5 kPa and -10 kPa are reasonable values for field capacity. For loam, -15 kPa is often quoted, and -33 kPa for clay. Compared with the orders-of-magnitude difference between field capacity and the permanent wilting point, such numerically small adjustments in matric potential may appear inconsequential. But as we'll see later in our study of the soil water characteristic curve, relatively small changes in matric potential in this part of the curve can drive large changes in volumetric water content.

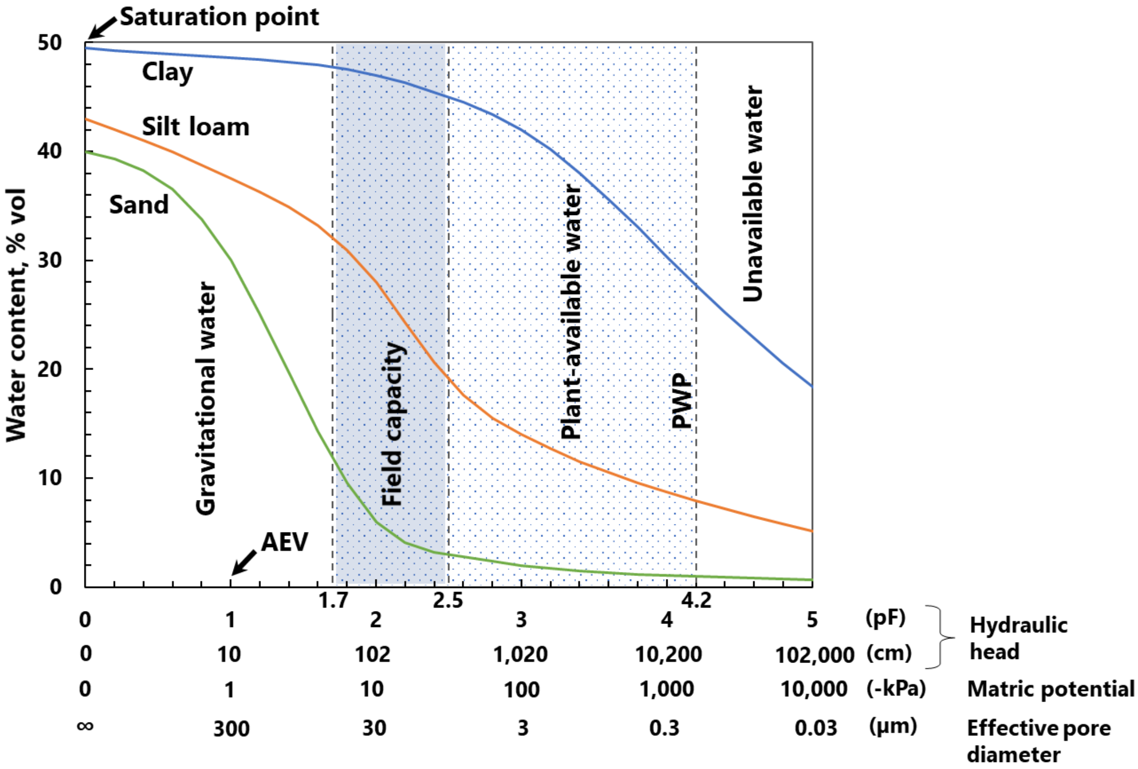


Figure 7.8.1 Generalized moisture retention curves for three soil composition types: sand, silt loam, and clay. The x-axis is scaled as: hydraulic head (cm H_2O at 4° C and logarithmic pF); matric potential (-kPa); and effective pore diameter (micrometers: µm), units commonly encountered in the technical literature. AEV = air-entry value; PWP = permanent wilting point. *Source: modified from Ehlers and Goss 2003.*

7.8 QUANTIFYING WATER RETENTION IN THE SOIL

Every substance that absorbs water has a characteristic way it gains and loses water. The bone-dry soil body is a heterogenous matrix of solids and air voids. Moist soil will exhibit a singular wetting and drying quality depending on the exact nature and distribution of solid particles, and the interaction of water with those particles. Even slight changes in mineral composition and packing can yield a water characteristic that is distinctive for that soil, like a human fingerprint. The relationship between soil water content, whether wetting or drying, and the energy status suspending that water *in situ*, i.e. matric potential, is given by the ***soil water retention curve*** (SWRC), three of which are displayed in **Figure 7.8.1.**

Investigators have given the SWRC names like soil water release curve, soil-water characteristic curve, drainage curve, and others, but they all describe the same ***non-linear function*** relating soil water content to the matric potential required to retain that content of water in the soil. The shape of the SWRC is governed by the number and size distribution of pores in the bulk soil, which is related to particle size distribution (% sand, silt, and clay) as well as factors like soil structure, degree of compaction, and organic matter content. As such, there is a continuous gradation of SWRCs for sand, silt loam, and clay soil which has important implications for land preparation via tillage, seedbed preparation and planting, scheduling irrigation, water budgeting, among other agronomic, hydraulic and geotechnical applications.

Let's begin by examining features in **Figure 7.8.1** that may look intimidating on first approach to SWRCs, but can, nonetheless, be described in plain language.

A SWRC is constructed like any graph of ordered pairs of values in that it has a vertical (ordinate: y-axis) and horizontal (abscissa: x-axis) component. The vertical component or y-axis in **Figure 7.8.1** is scaled to units of volume percentage (% vol), which represents a quantity of water. This quantity is the *volumetric water content* relative to the total pore volume of the soil, that is, a ratio multiplied by a factor of 100. Further, the unit % vol is numerically equivalent to *depth of water per unit depth of soil*, as described in TN 7 Part II Sec. 7.4.

The horizontal, or x-axis, in **Figure 7.8.1** has four different scales. The upper scale is ***hydraulic head*** expressed in pF units 0 to 5 including three fractional values. The pF scale is a logarithmic scale used to display values separated by orders of magnitude. Recall that pH is also a logarithmic scale of hydrogen ion concentration (see Technical Note 4); similarly, the pF scale is the base 10 logarithm of hydraulic head, which is measured as a depth (or length) of a hanging water column in centimeters at a given temperature (in this example, 4° C). For example, pF 1 is numerically equivalent to 10 cm water and pF 5 to 102,000 cm water. Below the pF scale are corresponding matric potential values in units of negative pressure, kilopascal (-kPa) described in TN 7 Part II Sec. 7.4. Each matric potential value on the x-axis corresponds to a fixed ***effective pore diameter***, calculated from the capillary rise equation, also from Sec 7.4. These values appear on the bottom scale.

There are four points of interest on the SWRC in **Figure 7.8.1.** These are:

- **Saturation point** This is the point where all the soil's pore space is effectively occupied by water. As noted in Section 7.7, at the saturation point capillary menisci are all flat and matric potential zero. Water retained between the saturation point and field capacity is ***gravitational water***, so-called because it drains beneath the root zone spontaneously under the influence of gravity and is, for the most part, unavailable to plants.
- **Air entry value (AEV)** This is the critical hydraulic head required to drain the largest soil pores. The exact air entry point lies somewhere between 7.5 and 15 cm H_2O (~pF 1.0 - 1.2) and depends especially on the soil structure. A low air entry value would infer relatively large drainage pores associated with a coarse-textured soil; whereas, above this value the soil remains saturated. The air entry value is also considered the height of the ***capillary fringe***, i.e. the highest point to which water can be suspended in a porous medium by capillary forces. Water retained between the AEV and field capacity is gravitational water.
- **Field Capacity** At field capacity, water is retained in the soil by adsorptive and capillary forces, and all movement of water by gravity has ceased (or is negligible). Thus, field capacity is often referred to as the soil water content "retained against the force of gravity". Field capacity is usually measured 2-3 days after rainfall, assuming that excess gravitational water has been allowed to freely pass through the subsurface soil layers. Field capacity is also called the *drained upper limit* (DUL). But as depicted in **Figure 7.8.1**, field capacity is not a fixed point on the SWRC but rather a zone roughly corresponding to suction heads between pF 1.7 and 2.5 (50 – 330 cm water). In sandy soils the suction at field capacity may be much lower, around pF 1.7-2.0 (50-100 cm H_2O), compared to a silt loam or clay soil where the suctions are closer to pF 2.2 – 2.5 (150 – 330 cm H_2O). **Figure 7.8.1** also makes clear the volume of water retained in a sandy soil at field capacity (around 12%) is much lower than a silt loam or clay soil.
- **Permanent Wilting Point (PWP)** At the wilting point, water is adsorbed so firmly (pF 4.2 or 15,000 cm H_2O) to the mineral particles, that it cannot be mobilized by plant roots. Below the PWP is the zone of hygroscopic water that is unavailable to plants. Although the PWP is shown as a fixed point, it too meanders (±) to some extent with clay content, compaction, and certain soil amendments. Most agronomic crops will suffer from irreparable loss or death if soil water content is allowed to reach the PWP. In many cases, losses in yield occur long before this point is reached. On the other hand, the wilting point for some desert plants has been measured down to pF 4.8 (60,000 cm H_2O). It would be great if we could engineer this trait into our field crops but alas, it's not yet possible.

Between field capacity and the permanent wilting point is the zone of ***plant available water (PAW)***. The maximum quantity of plant available water is calculated as the difference in water content between field capacity and the permanent wilting point. This quantity of plant available water corresponds to the soil's available water capacity assuming all the water in this zone is undiminished and at a low matric potential that can be overcome by plants. As mentioned earlier, field capacity does not last for long, so the amount of water remaining in the "plant available" bucket will change over time, a key factor differentiating plant available water from available water capacity.

What other information about the nature of water retention in the soil can be gathered from the curves in **Figure 7.8.1**?

First, coarse-textured soils have the steepest curve because water in these soils is bound mainly by capillary forces that break under higher matric potential (i.e. closer to zero). Thus water exhausts rapidly and the quantity of water remaining at field capacity is small. Soils with a high percentage of clay particles hold water primarily by stronger intermolecular adhesive bindings; water exhausts slowly and the amount of water at field capacity is large. Silty soils exhibit intermediate behavior at any given potential. Note that the vertical and horizontal axes in the graph can be reversed depending on what is being shown.

A criticism of SWRCs is that they portray the soil water as static components divided into gravitational, plant-available, and unavailable water. In reality, there is no requirement for doing this. Still, the concept has been valuable in the development of ideas for estimating the quantity of plant-available water after irrigation, the ***maximum allowable depletion*** of plant-available water, and irrigation timing and application rate.

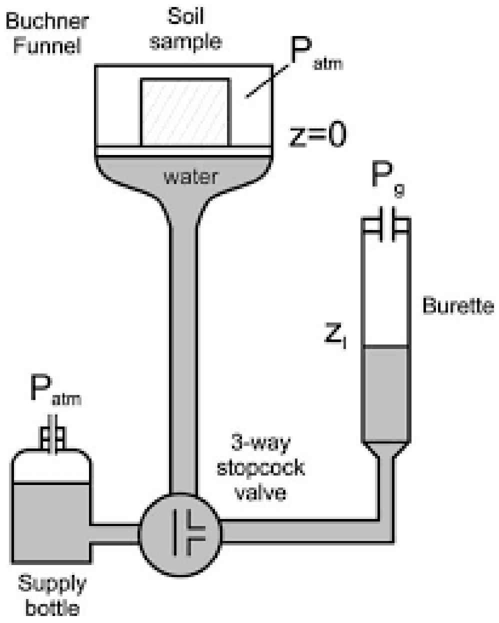


Figure 7.9.1 Schematic of a classical hanging water column or 'Haines apparatus'. *Image Source: Dane and Hopmans 2002.*

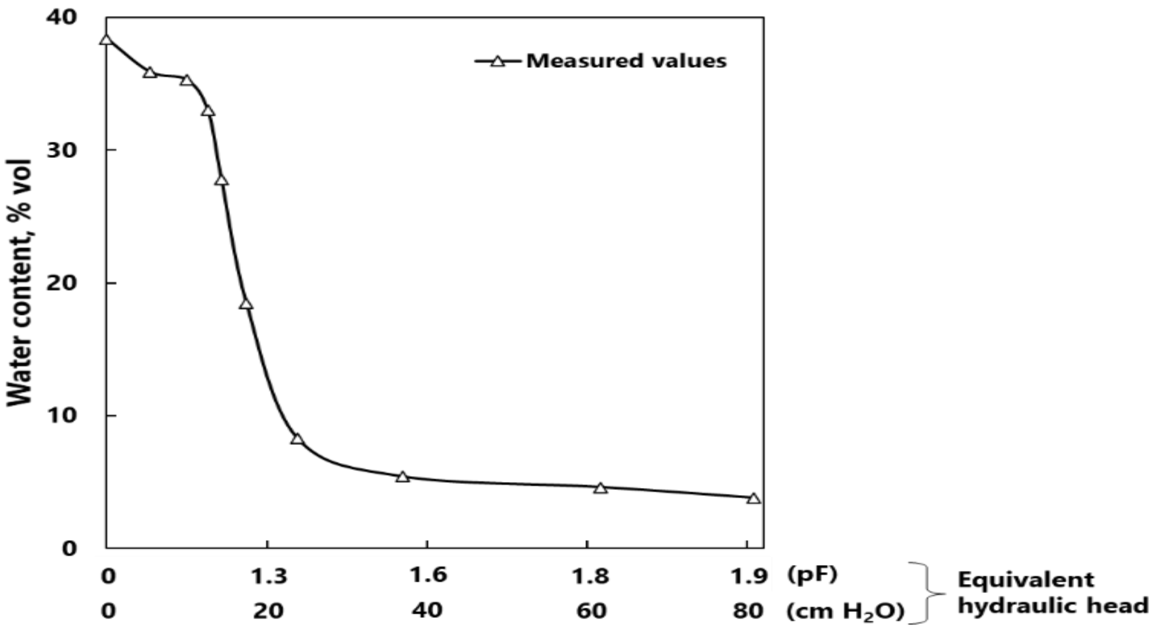


Figure 7.9.2 Water release characteristic of a sand soil described by the hanging water column or 'Haines apparatus' method. *Data Source: Rowell 1994.*

7.9 CONSTRUCTING WATER RETENTION CURVES

Soil water retention curves can be constructed by several methods. All are based on subjecting a wet sample to a known pressure head which is also assumed to be the soil matric potential. The pressure forces water to exit the sample and is registered as a change in length or mass. A classical method is the hanging water column, or 'Haines apparatus' shown in **Figure 7.9.1**. In the hanging column method, suction is created by adjusting the elevation of z_1 above or below a reference level, z_0. The measured distance between the height of the meniscus in the burette and the reference level is the applied suction.

One advantage of the hanging water column is that suction can be controlled with fine (1 cm or better) resolution and hence, water content can be determined at close suction intervals.

Figure 7.9.2 plots typical data from a Haines experiment. A disadvantage is the maximum suction that can be achieved is limited to between 200 and 250 cm equivalent hydraulic head due to practical considerations in adjusting the height of the water column. Therefore, the hanging water column technique is used to investigate water retention features of course-grained soils that drain easily at very low suction values. That is to say, water content at the air-entry point and field capacity can be determined for coarse-rained soils but other higher suction features like available water capacity and the permanent wilting point cannot.

A second method for generating a soil water retention curve employs a vacuum control or pressure outflow mechanism.

Figure 7.9.3 Tempe cells for determining the soil water characteristic between -10 and -100 kPa. Suction is applied to the soil column via supply tubing under controlled positive pressure. Water exits the column through a porous plate at the bottom until equilibration is reached. The applied pressure is assumed to be the matric potential of the column at that water content. Temperature must be controlled at all times during the procedure to minimize error from thermal dilation and contraction of water molecules.

Specimens are fully saturated, placed in a sealed chamber called a *Tempe cell* equipped with a special porous ceramic plate resistant to air entry. Specimens are then subjected to increasing capillary suction (**Figure 7.9.3**). Once equilibrium is reached, the water content of the sample is determined based on the volume of water that has exited the cell or change in mass of the sample. Tempe cells are best suited for investigating water release features of undisturbed specimens at matric potentials between -1 kPa and -100 kPa (10 cm and 1,020 cm H_2O). This is the pressure range sensitive to structural pore water retention in the soil. For matric potentials between -100 kPa and -1,500 kPa (1,000 cm and 15,000 cm H_2O), a sieved, homogenized sample is placed on specialized pressure plates housed within heavy-duty extractors (Figure 7.9.4).

A disadvantage of the Tempe cell-pressure plate approach is the time required for matric equilibration. This can range anywhere from 48 to 96 hours for matric potentials below 100 kPa (1,000 cm H_2O), depending on soil textural composition, to several weeks in a pressure plate apparatus.

Figure 7.9.4 Pressure plate extractors for determining the soil water characteristic between -1,000 and -1,500 kPa. Normally, disturbed samples are tested in a pressure plate extractor. This is justified because water retained in the soil at high potentials is associated with the mineral matrix whose physical properties do not vary significantly.

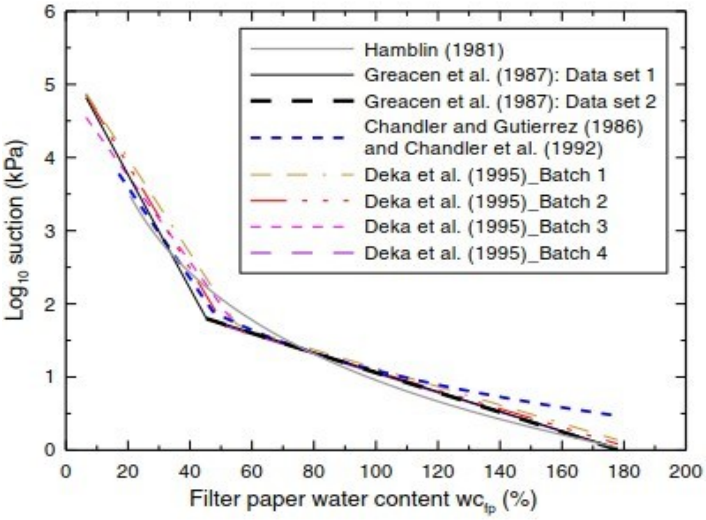


Figure 7.9.6 The water content-matric potential relationship of Whatman No. 42 filter paper from various test studies. Note that the curves are bi-linear with inflection point somewhere in the 40-50% wetting range. The log scale on the y-axis is given in pF units as explained in Section 7.7.1. *Source: Kim et al. 2015.*

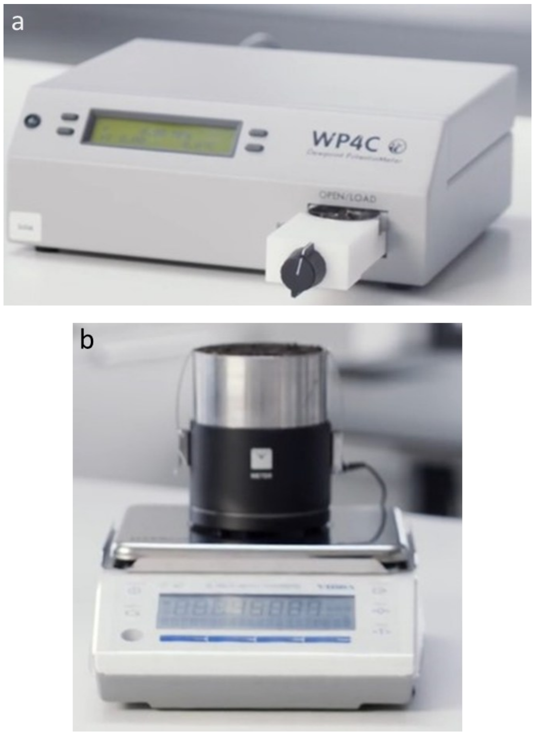


Figure 7.9.5 (a) Dewpoint potentiometer for dry side (-0.1 to -300 MPa) water release characteristic features. Unlike pressure plates, the dewpoint potentiometer is based on known thermodynamic relationships of dew point, temperature, and vapor pressure. **(b)** Wind/Schindler apparatus for wet-side (0 to -0.1 MPa) water release characteristics. *Image source: METER Group (link)*

Instruments like the dewpoint potentiometer (**Fig. 7.9.5a**) and the Wind/Schindler evaporative water flux measurement technique (**Figure 7.9.5b**) offer alternatives to traditional pressure plates.

A third method employing filter paper is based on the well-known water release characteristics of Whatman No. 42 paper (**Figure 7.9.6**). Several studies (Almeida et al. 2015; Chandler and Gutierrrez 1986; Deka et al. 1995) have validated filter paper as a low-cost alternative for constructing water retention curves but the method has not gained wide acceptance.

Figure 7.9.7 shows a typical plot of water retention data obtained by draining a saturated sandy clay loam soil under controlled outflow pressure. This curve has 10 measured values, each value representing the water content-matric potential relationship at equilibrium. We could have constructed the curve in reverse by re-wetting a soil that was initially dry, while equilibrating at the same points but the curve would not look the same. Why? The reason is due to a non-reversible property called ***hysteresis***. Note 7.9.1 further explains the phenomenon, but it should be pointed out that hysteresis per se doesn't void the utility of SWRCs in soil investigations. This is because it's reasonable to assume that drying conditions prevail in the soil following wetting via irrigation or rainfall (Hillel 1998). As long as the curve we're using is also a drying curve (most are), in-situ water content should not deviate appreciably.

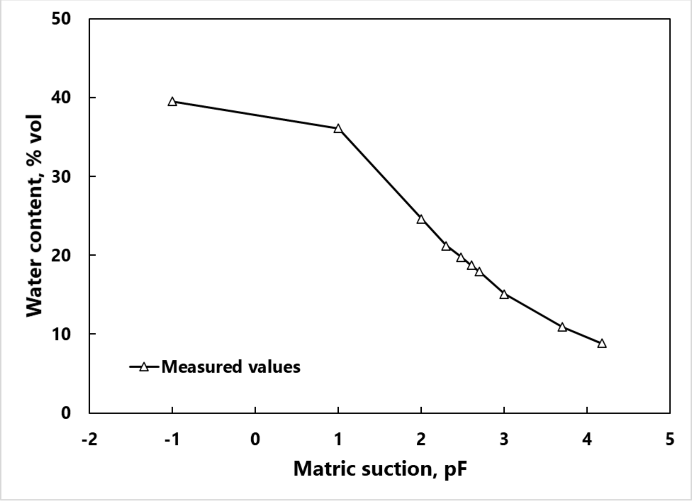


Figure 7.9.7 Plot of raw water retention data from a cultivated Wedowee sandy loam soil. *Source: Walters NCSU unpublished.*

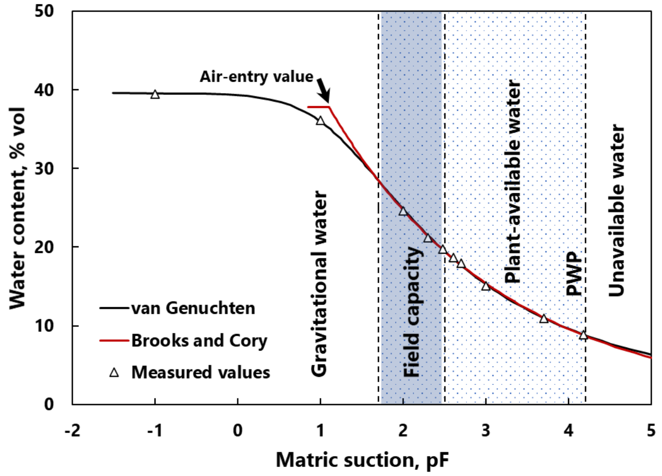


Figure 7.9.8 Plotted van Genuchten and Brooks and Cory SWRC models optimized via the RETC code using raw data from Figure 7.9.7. Principle soil water zones are marked in accordance with Figure 7.8.1.

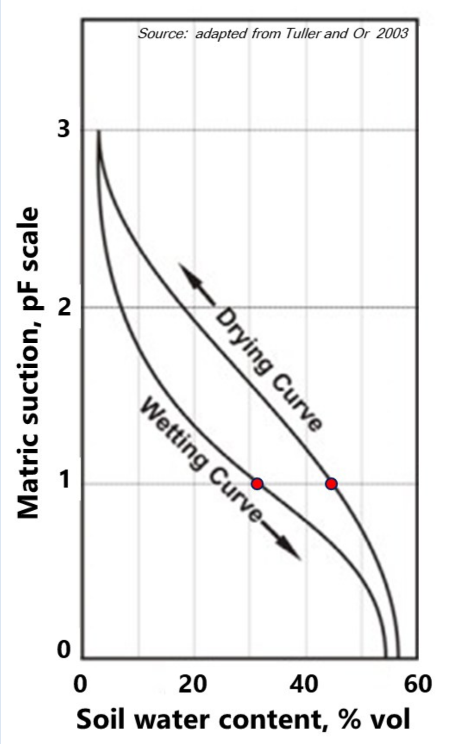
When constructing a SWRC, the general rule is the more points the better. In practice, there's a limit as to how many points can be measured due to the time required to equilibrate samples as mentioned above. Glancing back at **Figure 7.9.7**, we see a 10-point curve but what about the points in-between? How do we estimate the quantity of water at other matric potentials? Fortunately, methods have been developed to do just this.

The first method involves fitting a mathematical equation to the measured values to allow the calculation of water content for any unknown value on the curve. Several ***empirical*** equations describing the relationship between matric potential, hydraulic conductivity, and water content in unsaturated soil have been developed over the years. These equations are often referred to as "models". The most popular models are those by Brooks and Cory 1964, Campbell 1974, and van Genuchten 1980. While a full description of these model equations is beyond the scope of this Technical Note, it should be noted that freeware

Note 7.9.1

Hysteresis is a phenomenon that occurs in a system whose current state is dependent on its history. An example of hysteresis in the broad sense, is a tree branch that when weighted down, does not regain its original position after the weight is removed. In other words, the current state of the branch can't be predicted without knowing its history. Hysteresis is a fundamental property of magnetic materials, but can also be found in chemistry, biology, and yes, even in the soil.

Hysteresis exhibits two physical attributes: *irreversibility* and *lagging behind*. If a physical property Y depends on an independent variable X, the response of Y when X is increasing does not coincide with that for decreasing X. Such an irreversible process can be depicted as a loop, apparent in the wetting and drying branches of the soil water retention curves below.


Source: adapted from Tuller and Or 2003

It can be seen that the shape of the soil water retention curve depends on whether it follows a drying or wetting path. Also note that the water content at a given matric suction is not unique: at pF 1 (10 cm H_2O) the water content can have any value from 31% to 45% (symbolized by the red dots) depending on the soil's initial moisture content. Also note that water content on the wetting path is lower than (lags behind) the drying path between pF 0 and 3 (1 cm to 1,000 cm H_2O).

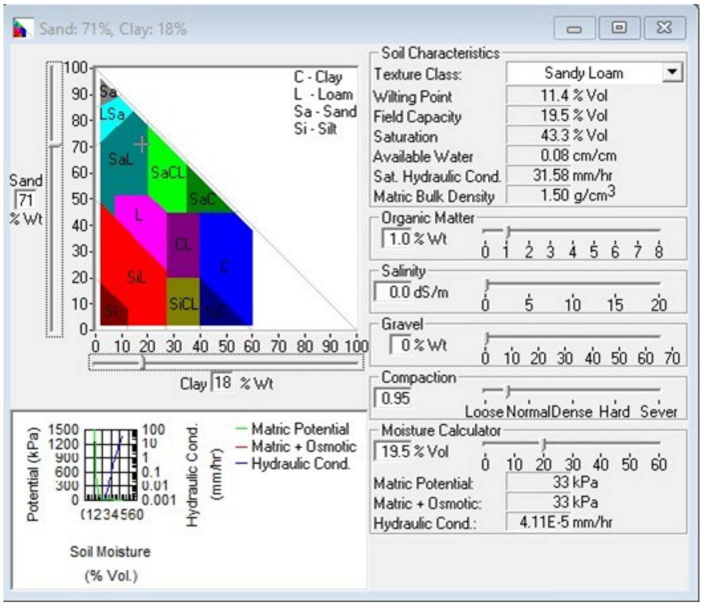
Haines (1930) first described the phenomenon of hysteresis in soil as irreversible sorption (wetting) and desorption (drying) pathways. Several factors have been identified as contributing toward hysteresis: the non-uniformity of individual soil pores, i.e. the "ink bottle" effect; entrapped air and shrinking and swelling factors affecting soil structure. While the phenomenon of hysteresis poses significant challenges in analyzing certain geotechnical problems, it has generally been ignored in agricultural water balance studies involving monotonic (constantly) wetting and drying processes in the soil.

programs like RETC can generate SWRCs from user-supplied matric potential and water content values according to van Genuchten, Brooks and Cory, and other mathematical models with no requirement for programming. **Figure 7.9.8** shows the optimized van Genuchten and Brooks and Cory models generated by the RETC code alongside the measured moisture retention values from **Figure 7.9.7**. As can be seen, the models attempt to find the best possible agreement between the measured and fitted values based on soil textural classification. In this experiment, the agreement is very close across a broad range of matric potentials from field capacity to the permanent wilting point. Also note the Brooks and Cory model ignores the saturation water content value while sharply dropping off at the air-entry point. The Campbell model (not plotted) is similar to Brooks and Cory.

The second method does not require any measurements for a particular soil. Here, knowledge of the soil textural classification (sandy loam, silty loam, clay, etc.) can be used to gain a general idea of the shape of the water retention curve. Parameters for the van Genuchten model equation have been evaluated for the major USDA soil textural classes (Sadeghi et al. 2018). These values can be substituted in the equation to construct a proxy SWRC for a similar soil. The Soil-Plant-Air-Water (SPAW) software program approximates soil water characteristics from easily determined soil properties like percentage sand, silt, clay, bulk density, and organic matter (**Figure 7.9.9**). SPAW and similar indirect solutions are a type of ***pedotransfer function***, whereby unknown soil properties are derived from their relationship to known properties.

7.10 USING WATER RETENTION CURVES

Once we have built a soil water retention curve, it's time to distill information from it. **Figure 7.9.10** is the same curve shown in **Figure 7.9.8** without the Brooks and Cory data. Appended on the right is a bar diagram marking the principal soil water zones after **Figure 7.7.2**.



Sand: 71%, Clay: 18%

Sand 71 % Wt

Clay 18 % Wt

Soil Characteristics

Texture Class: Sandy Loam

Wilting Point 11.4 % Vol

Field Capacity 19.5 % Vol

Saturation 43.3 % Vol

Available Water 0.08 cm/cm

Sat. Hydraulic Cond. 31.58 mm/hr

Matric Bulk Density 1.50 g/cm3

Organic Matter 1.0 % Wt

Salinity 0.0 dS/m

Gravel 0 % Wt

Compaction 0.95

Moisture Calculator 19.5 % Vol

Matric Potential: 33 kPa

Matric + Osmotic: 33 kPa

Hydraulic Cond.: 4.11E-5 mm/hr

Figure 7.9.9 Soil water characteristics calculator, a component of the Soil-Plant-Air-Water (SPAW) software program (link).

Note that a red dashed line has been added halfway between field capacity and the permanent wilting point. This line represents the water content at the maximum or management allowable depletion (MAD), defined as the percentage depletion of ***total available water (TAW)*** with no yield reduction for a specific crop. Also noted in the block diagram is the depth of water in each zone.

According to the SWRC in **Figure 7.9.10**, volumetric water contents for our sandy loam soil are:

$$\text{Saturation, } \theta_{SAT}\text{: } 0.396 \text{ cm}^3/\text{cm}^3$$

$$\text{Field capacity, } \theta_{FC}\text{: } 0.249 \text{ cm}^3/\text{cm}^3$$

$$\text{Permanent wilting point, } \theta_{PWP}\text{: } 0.088 \text{ cm}^3/\text{cm}^3$$

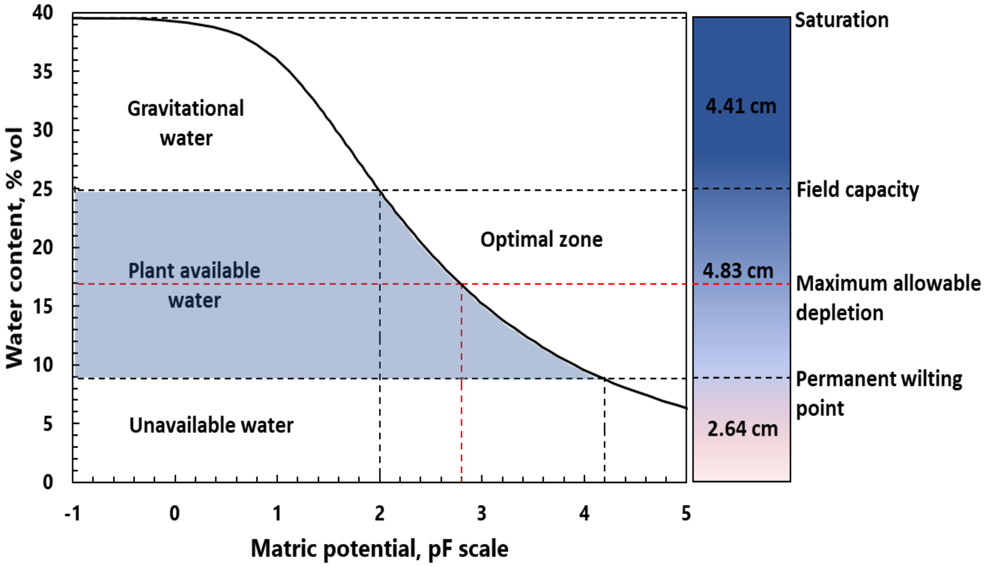


Figure 7.9.10 Soil water retention curve for a cultivated North Carolina Wedowee sandy loam soil with principal water zones demarcated. The shaded bar on the right indicates the depth of water in each zone through 30 cm deep. The horizontal and vertical red dashed lines represent the water content and matric potential values, respectively, for the maximum allowable depletion 50% level. Note that soil water content does not respond linearly to changes in matric potential, a crucial point to understand when interpreting sensor readings (VMC or MP). *Source: Walters NCSU unpublished.*

Recall from TN 7 Part II Section 7.4, that volumetric water content can be described as equivalent depth of water[1]. Here, we take 30 cm as the depth of soil, although it could be any depth of interest. Total available water is given by:

$$\mathrm{TAW} = (\theta_{\mathrm{FC}} - \theta_{\mathrm{PWP}}) \times z$$

where *z* is an arbitrary depth.

It can be seen that the amount of gravitational (i.e. drainage) water is 4.41 cm, available water capacity 4.83 cm, and 2.64 cm unavailable water. How were these numbers derived?

To answer, let's examine **Figure 7.9.10** in more detail.

Gravitational water takes the difference in water content between saturation and field capacity:

$$\text{Gravitational water} = \theta_{\mathrm{SAT}} - \theta_{\mathrm{FC}}$$

$$\frac{0.396 \text{ cm } \mathrm{H_2O}}{\text{cm soil}} - \frac{0.249 \text{ cm } \mathrm{H_2O}}{\text{cm soil}} = \frac{0.147 \text{ cm } \mathrm{H_2O}}{\text{cm soil}}$$

$$\times\ 30 \text{ cm soil} = 4.41 \text{ cm } \mathrm{H_2O}$$

Similarly, available water capacity takes the difference between field capacity and the permanent wilting point:

$$\text{Available water capacity} = \theta_{\mathrm{FC}} - \theta_{\mathrm{PWP}}$$

$$\frac{0.249 \text{ cm } \mathrm{H_2O}}{\text{cm soil}} - \frac{0.088 \text{ cm } \mathrm{H_2O}}{\text{cm soil}} = \frac{0.161 \text{ cm } \mathrm{H_2O}}{\text{cm soil}}$$

$$\times\ 30 \text{ cm soil} = 4.83 \text{ cm } \mathrm{H_2O}$$

And water content at the permanent wilting point is:

$$\frac{0.088 \text{ cm } \mathrm{H_2O}}{\text{cm soil}} \times 30 \text{ cm soil}$$

$$= 2.64 \text{ cm } \mathrm{H_2O}$$

The total water content is 4.41 + 4.83 + 2.64 = 11.88 cm. We can check this by dividing total water content by depth:

$$\frac{11.88 \text{ cm } \mathrm{H_2O}}{30 \text{ cm soil}} = \frac{0.396 \text{ cm } \mathrm{H_2O}}{\text{cm soil}}$$

which is equal to the water content at saturation *and* the soil's total porosity. Further, the water-filled porosity at field capacity is:

$$\text{Water-filled porosity} = \frac{\%\text{ water by volume, } \theta_v}{\text{total porosity}}$$

$$= \frac{24.9\%}{39.6\%} = 62.9\%$$

This figure is above the 'ideal' agricultural soil containing equal parts of air-filled (non-capillary) and water-filled (capillary) pore space. But it's not so high as to indicate waterlogged or poor drainage conditions, either.

For any water content between field capacity and the permanent wilting point, the percentage depletion is given by:

$$\%\mathrm{Dep} = \frac{(\theta_{\mathrm{FC}} - \theta)}{(\theta_{\mathrm{FC}} - \theta_{\mathrm{PWP}})} \times 100$$

$$= \frac{0.249 \text{ cm} - 0.169 \text{ cm}}{0.249 \text{ cm} - 0.088 \text{ cm}} \times 100$$

$$= \frac{0.08 \text{ cm}}{0.161 \text{ cm}} \times 100$$

$$= 50\% \text{ (rounded)}$$

where θ_{FC} and θ_{PWP} were defined as above, and θ is the fractional water content ($\mathrm{cm^3/cm^3}$) at the MAD. By definition, the percentage depletion is 0% at field capacity and 100% at the permanent wilting point.

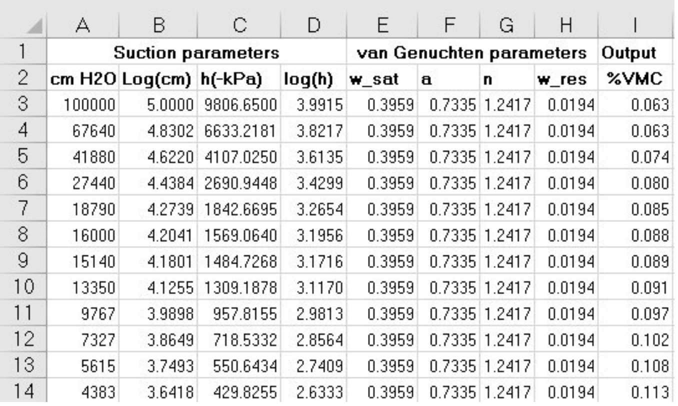
Depth of depletion at the MAD is calculated as:

$$\frac{\%\text{ Dep}}{100} \times \mathrm{TAW}$$

$$= \frac{50}{100} \times 4.83 \text{ cm } \mathrm{H_2O}$$

$$= 2.42 \text{ cm } \mathrm{H_2O}$$

Since we didn't measure water content at the MAD, its exact matric potential is unknown. This is where mathematical models come in handy. First, we loaded the equilibrated water content and tension values from our sandy loam soil into the previously mentioned RETC program then selected the van Genuchten model with the Mualem constraint (m=1-1/n). Upon execution, the code returns four parameter estimates and relevant statistical information from the program's optimization algorithm. Parameter estimates can be plugged into the equation to construct a whole or partial soil water release curve in a spreadsheet application like Excel (**Figure 7.9.11**). This way, the shape of the curve can be evaluated and computational errors, if any, detected.



	A	B	C	D	E	F	G	H	I
1	Suction parameters				van Genuchten parameters				Output
2	cm H2O	Log(cm)	h(-kPa)	log(h)	w_sat	a	n	w_res	%VMC
3	100000	5.0000	9806.6500	3.9915	0.3959	0.7335	1.2417	0.0194	0.063
4	67640	4.8302	6633.2181	3.8217	0.3959	0.7335	1.2417	0.0194	0.063
5	41880	4.6220	4107.0250	3.6135	0.3959	0.7335	1.2417	0.0194	0.074
6	27440	4.4384	2690.9448	3.4299	0.3959	0.7335	1.2417	0.0194	0.080
7	18790	4.2739	1842.6695	3.2654	0.3959	0.7335	1.2417	0.0194	0.085
8	16000	4.2041	1569.0640	3.1956	0.3959	0.7335	1.2417	0.0194	0.088
9	15140	4.1801	1484.7268	3.1716	0.3959	0.7335	1.2417	0.0194	0.089
10	13350	4.1255	1309.1878	3.1170	0.3959	0.7335	1.2417	0.0194	0.091
11	9767	3.9898	957.8155	2.9813	0.3959	0.7335	1.2417	0.0194	0.097
12	7327	3.8649	718.5332	2.8564	0.3959	0.7335	1.2417	0.0194	0.102
13	5615	3.7493	550.6434	2.7409	0.3959	0.7335	1.2417	0.0194	0.108
14	4383	3.6418	429.8255	2.6333	0.3959	0.7335	1.2417	0.0194	0.113

Figure 7.9.11 Spreadsheet with user-defined hydraulic input parameters, RETC-generated van Genuchten model parameters, and output (%VMC) calculated via the van Genuchten equation.

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[1] Volumetric water content can also be described as hydraulic head (cm H_2O).

Using the sandy loam SWRC depicted in **Figure 7.9.10**, an irrigator can see that matric potential at the 50% MAD level should be kept between pF 2 (-10 kPa) and pF 2.8 (-63 kPa). The field could be instrumented with soil moisture sensors programmed to trigger irrigation when soil water is approximately 16.9% (0.169 cm^3/cm^3). The amount of water needed to bring the soil to field capacity is 2.42 cm (~1 inch), which could be split in separate half-inch applications to minimize runoff.

Note that the recommended soil matric potential and allowable depletion are not fixed values but depend on soil type, crop, growth stage, climate, and economic factors. **Table 7.10.1** gives the recommended soil moisture potential (SMP) values for various crops at the MAD and **Table 7.10.2** the average percentages of allowable depletion of available soil water for crop water use of 5 mm (0.2")/day. These should be considered rough guidelines subject to further in-field calibration. For example, grain corn at the tasseling stage in North Carolina may consume 9 to 12.5 mm water per day. We would use a smaller MAD fraction, say, 0.40 rather than 0.55 shown in **Table 7.10.2**, at the most sensitive growth stage. This would put the irrigation interval every two days if corn roots were limited to 30 cm. However, crop roots may extend deeper than 30 cm in a uniform soil where there are no restrictive soil conditions. Therefore, we need to account for total available water through the ***effective root depth***, which is usually shallower than the ***maximum root depth***. This is done by averaging the SMP readings of two or more sensors placed in the crop rooting zone. Trigger points for irrigation can then be adjusted up or down accordingly.

Table 7.10.1 Recommended SMP values at the MAD for selected crops. SMP expressed as the absolute value (suction).

Crop	SMP (kPa or cb*)
Alfalfa	80-150
Cabbage	60-70
Cantaloupe	35-40
Carrot	55-65
Cauliflower	60-70
Celery	20-30
Citrus	50-70
Cotton	100-120
Maize (corn)-sweet	50-80
Small grain	
Vegetative stage	40-50
Ripening	70-80
Lettuce	40-60
Onion	45-65
Potato	30-50
Tomato	60-150

*centibars pressure: 1 kPa = 1 cb

Source: Hanson et al., 2000.

Table 7.10.2 Maximum allowable depletions (MAD) of soil water fraction and maximum root zone depth for selected crops.

Crop	MAD*	Maximum root depth (m)**
Alfalfa	0.55	1.0 - 2.0
Barley and oats	0.55	1.0 - 1.5
Beans-green and dry	0.45	0.5 - 0.9
Cabbage	0.45	0.5 - 0.8
Citrus	0.50	0.8 - 1.5
Cotton	0.65	1.0 - 1.7
Cucumbers	0.50	0.7 - 1.2
Maize (corn)-grain	0.55	1.0 - 1.7
Maize (corn)-sweet	0.50	0.8 - 1.2
Onions	0.30	0.3 - 0.6
Peanut (groundnut)	0.50	0.5 - 1.0
Potatoes-Irish	0.35	0.4 - 0.6
Potatoes-sweet	0.65	1.0 - 1.5
Rice	0.20	0.5 - 1.0
Sorghum-grain	0.55	1.0 - 1.2
Sorghum-sweet	0.50	1.0 - 1.2
Soybeans	0.50	0.6 - 1.3
Sweet melons	0.40	0.8 - 1.5
Sweet peppers	0.30	0.5 - 1.0
Tomato	0.40	0.7-1.5
Turf grass-warm season	0.50	0.5 - 1.0
Turf grass-cool season	0.40	0.5 - 1.0
Wheat-spring and winter	0.55	1.0 - 1.8

*Values for crop water use of 5mm (0.2")/day

**Effective rooting depth is usually shallower due to soil and other factors.

Source: Allen et al., 1998.

7.11 CROP ROOT ZONES

Rooting depth varies with crop and growth stage. **Table 7.10.2** gives the maximum depths to which various mature crops will extract available water. As noted previously, available water in the effective root zone is what we're after and this is usually shallower than the maximum due to soil and other factors. The maximum root zone depth of crops determined in **Table 7.10.2** are from the classical FAO Irrigation and Drainage Paper No. 56 and reflect an international view. As such, regional maximum and effective root depths may be shallower and, if such data are available, these should be consulted. Two good sources of regional information for North America are the USDA-NRCS National Agronomy Manual (Table A1) and for the Southeast, the North Carolina Irrigation Guide (Table A2).

Root water extraction in a uniform soil is often approximated by the 'quarter rule'. It states that 40% of water is extracted from the upper 25% of the root zone, 30% from the next, 20% from the next, and 10% from the lowest quarter (**Figure 7.11.1**). That is, about 70% of the water used by crops comes from the upper half of the rooting zone. This zone is called the *effective root depth*.

Roots will extract water from deeper in the soil but under free drainage conditions there is usually insufficient water in the lower zones to maintain optimum growth.

The maximum rooting depth of corn in North Carolina is about 1.2 m (4 feet). We know from prior field investigations that our Wedowee sandy loam soil has a dense, brittle zone about 60 cm deep limiting root extension. What is the total available water capacity and the depth of water at 40% maximum allowable depletion assuming uniform soil conditions and 70% of the freely available water is contained in this 60 cm rooting zone? How many days between irrigations if evapotranspiration (ET) is 9 mm/day and there is no rainfall?

Solution:

$$\begin{aligned}\text{TAW} &= (\theta_{\text{FC}} - \theta_{\text{PWP}}) \times z \\ &= \left(\frac{0.249 \text{ cm H}_2\text{O}}{\text{cm soil}} - \frac{0.088 \text{ cm H}_2\text{O}}{\text{cm soil}}\right) \times 60 \text{ cm soil} \\ &= \frac{0.161 \text{ cm H}_2\text{O}}{\text{cm soil}} \times 60 \text{ cm soil} \\ &= 9.66 \text{ cm H}_2\text{O}\end{aligned}$$

Depth of depletion at 40% MAD:

$$\begin{aligned}&\frac{\%\text{ Dep}}{100} \times \text{TAW} \\ &= \frac{40}{100} \times 9.66 \text{ cm H}_2\text{O} \\ &= 3.86 \text{ cm H}_2\text{O}\end{aligned}$$

Number of days between irrigations:

$$\begin{aligned}&3.86 \text{ cm H}_2\text{O} \div \frac{0.9 \text{ cm H}_2\text{O}}{\text{day}} \\ &= 4.3 \text{ days or every 4 days}\end{aligned}$$

That is, to avoid stress and inevitable yield loss, we'll need to irrigate our corn crop every four days.

Note that it's not necessary to maintain soil water content at field capacity, just within the optimal "no-stress" zone. Tensiometers and/or moisture sensors can be deployed to monitor water availability in the effective root zone during the growing season (see Note 7.11.1). The actual depth of water applied at each irrigation event is governed by the soil's ***infiltration rate***, a property that can vary tremendously depending on factors like texture, sodicity, compaction, organic matter, the presence of restrictive zones or a perched water table. A general rule of thumb is that fine-textured, loamy soils with a low intake rate should be irrigated more frequently with short bursts of water whereas, sandy loams can accept longer runs spaced further apart. Again, the importance of local testing is emphasized.

But what if the soil is non-uniform? How do we determine TAW?

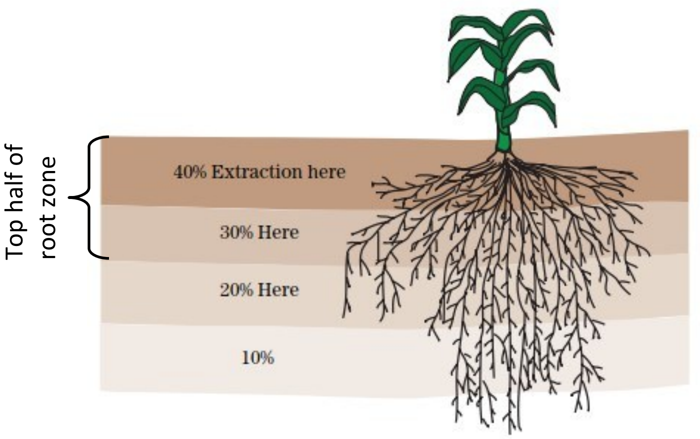

Figure 7.11.1 Illustration of the quarter rule of soil water extraction and effective root depth. *Source: NRCS National Agronomy Manual 2011.*

Many soils have distinct "horizons" i.e. natural layers that differentiate them by color, texture, chemical and/or physical properties[3]. In turn, each horizon may have different water characteristics. The total available water (TAW) in a soil profile is the sum of the products of the AWCs and the horizon thickness:

$$\text{TAW} = \sum_{i=1}^{n} \Delta z_i \times \text{AWC}_i$$

where

Δz = thickness of soil horizon, cm

i=soil horizon number

n=number of horizons

Readily available water (RAW) is defined as the total depth of plant-available water per unit surface area between irrigation events:

$$\text{RAW} = \text{TAW} \times \text{MAD}$$

Readily available water for a non-uniform soil can be found by summing the products of the AWCs and horizon thickness as above, multiplied by the maximum allowable depletion.

Ideally, studies should be done to analyze soil hydraulic properties before designing an irrigation or drainage system. Nonetheless, it's not always possible to describe the entire soil profile in detail due to factors like time, cost, or laboratory facilities. An alternative would be to use published sources of soil information like Web Soil Survey (WSS, link) hosted by the U.S. Department of Agriculture. The WSS is an interactive tool for delineating different soil mapping units in an area of interest (AOI). Once the mapping unit has been identified, descriptive information about the soil can be found at the soil series level. This information, combined with the Soil-Plant-Air-Water tool mentioned in Section 7.7.2, can yield reasonable approximations of hydraulic properties.

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[3] Naturally occurring soil layers are called horizons. The descriptor 'layer' is usually reserved for engineered soils or soils that have been remixed or manipulated in some way.

Core Intelligence

Available Water Capacity (AWC): The specific soil water content between field capacity (FC) and the permanent wilting point (PWP) expressed as a fraction or percentage of soil volume:

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

where

AWC = available water capacity, fraction or percent

θ_{FC} = volumetric water content at field capacity

θ_{PWP} = volumetric water content at the permanent wilting point

AWC is a practical indicator of water storage capacity across different soil types. Soils with a high percentage of silt have the highest AWC whereas soil with a high percentage of coarse particles, e.g., sandy soils, have the lowest AWC. Clay soils have an AWC intermediate between silty and sandy soils (see Table 7.7.1). The AWC of clay soils is less than silty soils because a larger percentage of water in clay soils is held too tightly to be used by plants.

Capillary fringe: Zone immediately above the water table that is saturated, but under sub-atmospheric pressure (tension). Its height varies inversely with the average soil pore size. The top of the capillary fringe is also the point corresponding to the air entry value (AEV) required to drain the largest soil pores.

Effective pore diameter: The equivalent pore size value calculated from the capillary rise equation:

$$h = \frac{2\gamma\cos\theta}{\rho g r}$$

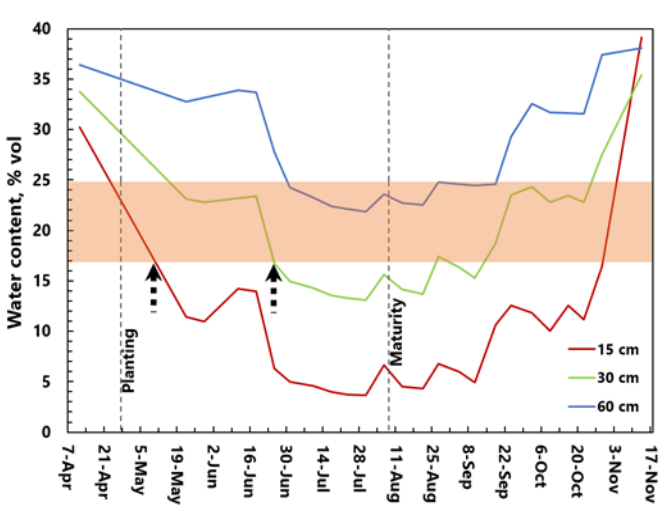
where h is the height of water lifted in a capillary tube. The capillary rise equation (also called Jurin's Equation) relates matric potential, symbolized by h, inversely with given radius r. If the equation is re-arranged to solve for r, this value multiplied by 2 gives the effective pore diameter. See TN 7 Part II Section 7.4 for more information.

Effective root depth: The upper portion of the root zone where plants get most of their water. Effective rooting depth is estimated as one-half (50%) of the maximum rooting depth.

Empirical: Based on observed measures or values from experimentation, not theory. An empirical model describes a type of object or system not attributing to knowledge of its composition or internal mechanisms. The parameters of an empirical model may have no physical meaning even though correlated with properties exhibited by an object or system. A *theoretical* model describes a type of object or system by attributing to it knowledge of its composition or internal mechanisms, such that reference to its behavior can be explained by that knowledge alone. Empirical vs. theoretical is an important distinction in probability, statistics, physics, and other areas of inquiry.

Note 7.11.1

The following chart illustrates seasonal profile soil water content from a Delta-T multiple depth moisture sensor installed in a non-irrigated, conventional disk tillage maize plot under free drainage. It's the same sandy loam soil described by the soil water retention curve in Figure 7.9.10.



The shaded area is 50% maximum allowable depletion (MAD) determined for this soil. Vertical dashed lines are planting and maturity dates. Dashed arrows indicate where water content readings are less than the MAD and where irrigation should begin. At the start of the season readings are high from winter and spring rains. Note that the 15 cm depth is the first to dry out followed by the 30 cm and 60 cm depths. The temporal lag at 30 cm is due to fewer roots penetrating to this depth at early growth stages. Readings indicate that only partial irrigation through 15 cm was needed up until June 28, while soil water content at 60 cm was never less than 50% MAD thus in no need of replenishment. Partial re-wetting of the profile occurred after rainfall, but the amount was not enough to bring readings back to 50% MAD. The drying cycle bottomed around maturity followed by gradual re-wetting starting in late August. By November, soil water content approached the saturation point (39.6%). Grain yield in this season averaged 3.6 Mg/ha (57 bu/acre), a fraction of maize potential yield. Collectively, these data point up that dryland cropping cannot hope to feed a growing population nor sustain farm profitability. *Data source: Walters NCSU unpublished research.*

Field Capacity: The amount of water remaining in the soil after free drainage, denoted θ_{FC}. Water entering the soil from irrigation or natural precipitation initially moves downward due to the pull of gravity. The point at which drainage ceases (or becomes very small) is determined by soil particle shape and the packing density of the particles. Water remaining in the soil after free drainage is then held by capillary forces (adhesion and the surface tension of water molecules) and represents its water content at 'field capacity'. A sandy loam soil reaches field capacity when matric potential is near -10 kPa. Medium to fine-textured soils reach field capacity near –33 kPa matric potential. Field capacity is mainly used to infer soil physical attributes like workability or available water capacity as related to water content Field capacity is reached in most agricultural soils within 24 to 48 hours after wetting providing there are no restrictive layers.

Gravitational water: Water in the soil that is free to drain or move due to the forces of gravity. The value for gravitational water is given by:

$$\mathrm{GW} = \theta_S - \theta_{FC}$$

where

GW = gravitational water, fraction or percent

θ_{SAT} = volumetric water content at saturation

θ_{FC} = volumetric water content at field capacity

Gravitational water is usually not available to plants, particularly in sandy soils with rapid (< 2 days) drainage.

Hydraulic head*:* It represents the mechanical energy per unit weight of the fluid in the system. Hydraulic head is defined as:

$$h = h_p + h_z$$

where h is the *hydraulic* head, h_p is the *hydrostatic pressure* head and h_z is the *elevation* head. All three quantities have the dimension of length [L]. The pressure head represents the energy due to fluid pressure, and the elevation head represents the gravitational potential energy arising from elevation. Water flows from high to low hydraulic heads in accordance with the second law of thermodynamics. Hydraulic head is a key parameter describing the mechanical energy state of a hydraulic system.

Hygroscopic water: The fraction of water left in the soil beyond -3 MPa (30 bars; 29.6 atm; 435 psi) that is adhered very strongly to soil particle surfaces in equilibrium with water in the atmosphere under specific relative humidity and temperature conditions (typically 98% and 25°C). Hygroscopic water exists in the form of a vapor, not liquid water. Usually, the only way to remove it is by drying soil at 105°C until a constant weight is obtained. Some investigators consider all water held at tensions greater than the permanent wilting point (-1.5 MPa) as hygroscopic water though, strictly speaking, this isn't true. However, all water held at tensions greater than the permanent wilting point including hygroscopic water, is unavailable to plants. Hygroscopic water is sometimes referred to as *residual water* or *residual water content.*

Hysteresis*:* An irreversible retarding effect when the forces acting upon a body are changed. It represents the history dependance of physical systems that change depending on the starting point used to observe them. In the soil system, hysteresis is observed in different water retention curves describing soil water content vs. matric potential when the soil is gaining or losing water.

Infiltration rate*:* The rate at which water infiltrates the soil, where *infiltration* describes the entry of water into the soil body at the surface. Units of measure are length (centimeters or equivalent)) per unit time (seconds, hours, etc.). Normally, infiltration rate is high at the beginning of a rainfall or irrigation event and decreases over time as the soil gets wetter. Infiltration rate varies with soil physical properties and surface conditions (sealing, crusting, presence of biopores, etc.).

Maximum Allowable Depletion (MAD)*:* It represents the depth or volume fraction of total available water (TAW) that can be removed from the soil without significantly affecting plant growth and development.

Maximum root depth*:* The deepest potential root depth expected by a crop under specific soil conditions. Physical or chemical barriers in the soil may limit the actual root depth to something less than the potential depth (see effective rooting depth).

Non-linear function*:* A mathematical relationship between two variables that is not proportional. The graph of a linear function is a straight line whether it is increasing or decreasing whereas, the graph of a non-linear function is a curved line. Thus, the variables or 'parameters' of a linear function have no exponents different from 1 (known as first order or degree). The soil water retention curve is non-linear because the equations describing it all have variables with exponents different from 1.

Pedotransfer function*:* A statistical tool allowing the estimation of state and/or composition by measuring a soil property that has a relationship to some other unmeasured property. Pedotransfer functions are often used to estimate unknown soil properties when direct measurement is difficult, expensive, or time consuming.

Permanent Wilting Point (PWP)*:* Defined as the lower limit of plant available water below which plants lose turgor pressure and cease growing even under conditions of zero transpiration. It is usually denoted θ_{PWP} or θ_{WP}. For many crops, the PWP corresponds closely to a matric water potential of −1.5 MPa. The upper limit of plant available water is defined as field capacity; and the difference between field capacity and the permanent wilting point is the plant-available water capacity for a soil. The upper and lower limits of water availability drive many important soil hydrologic processes related to plant physiological response, irrigation and water management, and agronomically important soil-plant-water relations.

Plant Available Water (PAW)*:* The equivalent depth of water which is currently available to plants within a given soil layer. The value for PAW is given by:

$$\mathrm{PAW} = (\theta_C - \theta_{WP}) \times z$$

where

PAW = plant available water [cm, m, inches]

θ_C = current value of volumetric water content

θ_{WP} = volumetric water content at the permanent wilting point

z = thickness of the soil layer

Since volumetric water content is also a depth, PAW is typically expressed as a depth of water per unit depth of soil. PAW differs from AWC in that it accounts for water status across soil types at any value of volumetric water content.

Readily Available Water (RAW): Defined as the total depth [cm, m, inches] of plant-available water per unit surface area between irrigation events. RAW is equal to total available water (TAW) multiplied by the maximum allowable depletion (MAD):

$$\mathrm{RAW} = \mathrm{TAW} \times \mathrm{MAD}$$

Saturation point: Generally speaking, the stage of something where it can no longer acquire or take on more of something else. In a soil, the saturation point is defined as the fractional water content (% vol) when all its pore space is filled with liquid water, denoted θ_{SAT}. It is, therefore, the degree of wetness beyond which no further addition of water is possible. The saturation point of soil varies substantially with texture ranging from 10-15% vol for very coarse-grained sands to 55% vol for fine-grained clays. The fractional water content at the saturation point determined for the North Carolina sandy loam soil depicted in figure 7.9.10 is 39.6% vol.

Soil Water Retention Curve (SWRC): A graph describing the relationship between soil water content and matric potential. Each soil has a unique SWRC that identifies it, analogous to a human fingerprint. Curves can be plotted from *in-situ* or laboratory measured points or generated from special non-linear equations that attempt to model the relationship. Also called *soil water characteristic curve*, *drainage curve*, *soil moisture release curve*.

Total Available Water (TAW): The depth of water in the soil available for plant growth. It is also the soil's water holding capacity (WHC). Total available water is given by:

$$\mathrm{TAW} = \mathrm{AWC} \times z$$

where

TAW = total available water or water holding capacity of the soil [cm, m, inches]

AWC = available water capacity, fraction or percent

z = effective root zone depth [cm, m, inches]

FURTHER READING

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