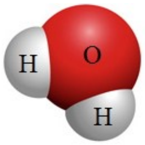
TECHNICAL NOTE 7.
AG WATER LITERACY II



7.4 DESCRIBING AND MEASURING SOIL WATER

Agriculture, whether dryland or irrigated, is organized around the simple premise of maintaining adequate reserves of water in the soil root zone at all stages for utilization by plants. Global climate models also depend on quantifying soil water content to calibrate drought risk scenarios and to evaluate short- and long-term trends. But how do we quantify water in the soil? Is the amount of water too little, too much, or exactly right? When is it time to irrigate, and by how much? To answer these questions, we must find a way to describe and measure soil water itself.

Water in the soil can be described two ways:

- water content
- water potential

Water content describes the state of water in terms of physical matter, i.e. the *mass* of H_2O in a substance. The term ***mass*** is reserved herein to mean ***weight***, but recall that in classical physics the mass of a body is fixed whereas weight is proportional to the strength of the gravitational field in which the body is measured. Water potential, in contrast, describes the state of water by reference to its *energy status*. Both expressions have myriad applications in agronomics and engineering and, as explained in Technical Note Part III, can be related. Here we focus on the quantitative description of mass, mass fraction, volumetric conversion, and energy status applied to soil water.

Mass water content measures water, the substance, in the soil directly by weighing a wet sample before, and after, drying for 24 hours at 105°C:

$$\theta_m = \frac{M_w}{M_s} \qquad [\text{Eq.}1]$$

where M_w is the gram (g) mass of liquid water evaporated from M_s, the oven-dry solid gram mass of soil. The mass of liquid water, symbolized by θ_m, is expressed as a decimal fraction of the soil solid mass with units gram per unit gram, abbreviated g/g[1]. The mass fraction of water is called ***gravimetric*** water content, symbolized by θ_g. The initial mass of wet soil is arbitrary.

Measuring gravimetric soil water content can be done at any time for any purpose. In this sense gravimetric water measures the current or ***in-situ*** water content under prevailing conditions.

Example 1 An investigator sampled a field soil 10 cm deep. A sub-sample was taken and immediately weighed, placed in a sealed tin, and dried until no further change in mass was detected. The measurements were reported as:

wet soil weight + tin = 1,750 g
oven-dried soil + tin = 1,500 g
weight of the tin = 50 g

The gravimetric SWC calculated per Eq. 1 is:

$$\theta_g = \frac{M_w}{M_s} = \frac{M_{wet} - M_{oven-dry}}{M_s - M_{tin}}$$

where the mass of water, M_w, equals the mass of wet soil M_{wet} minus the mass of oven-dry soil $M_{oven\text{-}dry}$, and the mass of soil solids, M_s, equals the mass of the oven-dry soil + tin minus the mass of the tin:

$$\theta_g = \frac{1{,}750\text{ g} - 1{,}500\text{ g}}{1{,}500\text{ g} - 50\text{ g}} = \frac{250\text{ g}}{1{,}450\text{ g}} = \frac{0.172\text{ g } H_2O}{\text{g soil}}$$

The mass water percentage, $P_m = \theta_g \times 100 = 17.2\%$

Gravimetric water content states that each gram of soil contains 0.172 grams H_2O. How should we interpret this?

Gravimetric water content can be compared to the mass of two bodies at rest in **Figure 7.4.1**. In this sketch the mass of water weighs less than the mass of bulk dry soil, so the balance tips in favor of soil whereas the water is suspended aloft.

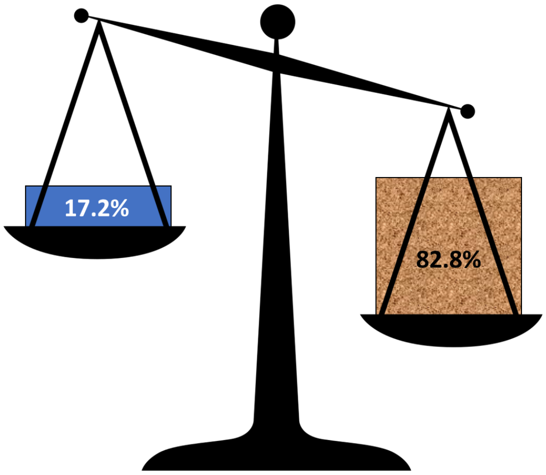


Figure 7.4.1 Gravimetric water content simply compares the mass of water to the mass of dry soil.

Because gravimetric water content does not depend on the volume of soil, samples can be collected with a shovel, auger, drive tube, or what have you (See Technical Note 19 for a description of common tools for collecting soil samples).

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[1] Centimeter-gram-second (cgs) system of units. In some fields the meter-kilogram-second (mks) system is preferred. In this and other Technical Notes we employ both systems following common scientific or engineering usage.

Gravimetric water content is time consuming and expensive as it relies on direct measurement in the field or laboratory. Because of these limitations, numerous indirect methods (also called "surrogate" methods) have been developed to measure soil water content ***in situ*** (see Note 7.4.1). On the other hand, the gravimetric method is highly accurate and a reference method for water content determination by consensus bodies like the United States Department of Agriculture (USDA), Association of Official Agricultural Chemists (AOAC), and American Society for Testing and Materials (ASTM). Water content can also be estimated by feel and appearance where a field sample is manipulated in hand by an experienced person. This method requires the expert knowledge of soil properties, i.e. ***strength***, ***plasticity***, ***dilatancy***, ***wetness color*** and is considered a qualitative approximation, not a measurement per se of water content.

Gravimetric water content can be converted to volumetric water content by multiplying by the soil dry bulk density:

$$\theta_v = \theta_g \times \frac{\rho_b}{\rho_w} \qquad [\text{Eq. 2}]$$

where

θ_v is the volumetric water content, cm^3/cm^3

θ_g is the gravimetric water content, g/g

ρ_b is the bulk (dry) density, g/cm^3

ρ_w is the density of pure water, 1 g/cm^3 @ 4 ° C

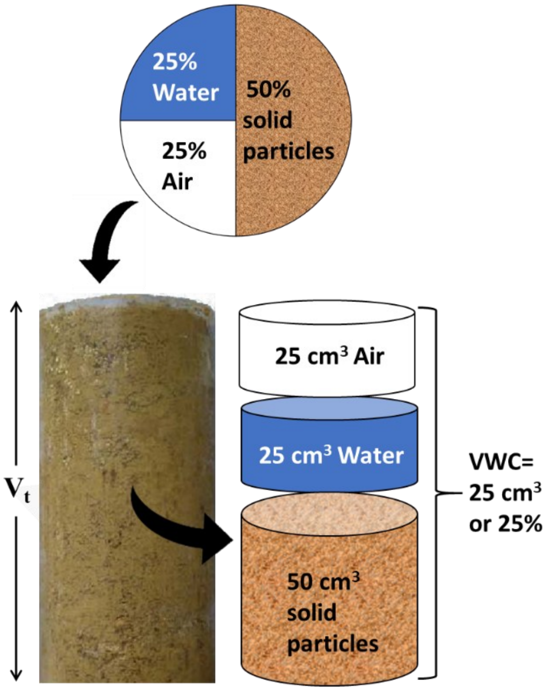
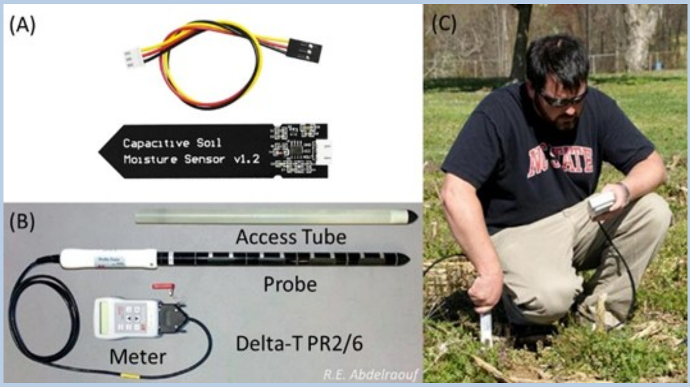


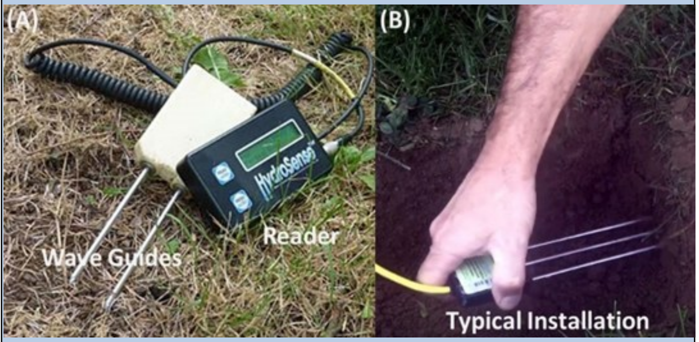
Figure 7.4.2 Division of a soil body into solid, water, and air fractions. At top, a two-dimensional pie chart with "ideal" soil composition. Below, an actual soil core of volume Vt as it would appear divided into respective fractions. The volumetric water content (VWC) is 25 cm^3 or 25%.

NOTE 7.4.1

Indirect (surrogate) methods of determining in-situ soil water content measure another variable that is affected by soil water content and then relates changes in that variable with changes in water content. The dielectric permittivity of water (see TN Part I Section 7.2) is an electromagnetic (EM) property used to measure soil water content. Dielectric methods take advantage of the difference in bulk permittivity of three soil components: ordinary liquid water (~80), air (~1) and mineral particles (~4). This contrast makes dielectric permittivity a highly sensitive indicator of soil water content. As permittivity changes, sensors can relate the change with soil water content. Two widely deployed permittivity sensors are described below.



Capacitive soil moisture sensors derive relative dielectric permittivity by measuring the frequency-dependent capacitance, or ability to store electrical charge, of the bulk soil surrounding the sensor. Sensors are available as single depth (inset A) or segmented multiple depth or down hole probes (inset B) . Sensors may be buried directly in the soil or inserted into a pre-installed access tube (inset C). Sensors can be integrated with dataloggers, DIY hardware like Arduino and Raspberry Pi, and wireless telemetry services for remote, real time soil moisture monitoring. Capacitance probes are sensitive to soil properties and require soil-specific calibration for highest accuracy.



Time domain reflectance (TDR) sensors derive relative dielectric permittivity by measuring the velocity and amplitude of a fixed-frequency EM wave traveling back and forth on metallic wave guides (inset A). Probes may be installed vertically or horizontally (inset B). TDR sensors acquire high accuracy volumetric soil moisture values without the need to perform a soil-specific calibration. TDR-like sensors, e.g. the GroPoint Profile, use internal looped guides and can be installed with minimal soil disturbance. Advanced capacitance- and TDR-based probes log soil moisture content continuously with remote monitoring capability.

Other surrogate methods include the neutron moisture meter and heat pulse sensors. The neutron meter requires expert training on radioactivity and is not commonly deployed outside engineering and research applications.

Volumetric water content also depends on two other values: the dry ***bulk density*** of soil and, the density of water. Bulk density (symbol: ρ_b) is defined the ratio of the mass of a given dry soil sample to its bulk volume:

$$\rho_b = \frac{M_s}{V_t} \qquad \text{[Eq. 3]}$$

where

Ms is the oven-dry soil mass, g

Vt is the soil volume, cm³

Similarly, the density of water is defined as the ratio:

$$\rho_w = \frac{M_w}{V_w} \qquad \text{[Eq. 4]}$$

where

M_w is the mass of water, g

M_v is the volume of water, cm³

Understanding how gravimetric water content is converted to volumetric water content can seem a bit non-intuitive to the novice dirt hog. The following describes the steps in the conversion starting with Eq. 2 above:

$$\begin{aligned}\theta_v &= \theta_g \times \frac{\rho_b}{\rho_w} \\ &= \frac{\theta_g \rho_b}{\rho_w}\end{aligned}$$

Eq. 2 can be expanded following:

$$\frac{\theta_g \rho_b}{\rho_w} = \frac{\left(\frac{M_w}{M_s}\right)\left(\frac{M_s}{V_t}\right)}{\left(\frac{M_w}{V_w}\right)} = \left(\frac{\cancel{M_w}}{\cancel{M_s}}\right)\left(\frac{\cancel{M_s}}{\enclose{circle}{V_t}}\right)\left(\frac{\enclose{circle}{V_w}}{\cancel{M_w}}\right) = \frac{V_w}{V_t} = \theta_v$$

Note that gravimetric water content θ_g in Eq. 2 can be written as the ratio M_w/M_s (from Eq. 1). Similarly, bulk density can be written M_s/V_t and the density of water M_w/V_w. Dividing fractional values requires that we take the divisor, in this case M_w/V_w, and multiply by its reciprocal value, canceling units where appropriate. This is indicated by the red and green slash operators shown above. What's left after cancelling units is the ratio V_w/V_t which is the volume of water divided by the soil volume. This defines the fractional volume of soil occupied by water, or θ_v as depicted in **Figure 7.4.2**.

In making this conversion, two things must be observed. First, the soil volume V_t must be known. Generally, this information is obtained by measuring the volume of the sampling tool or excavation hole which is needed to determine soil bulk density (see Technical Note 2 for details about tools, bulk density measurement and calculations). Failing that, "average" values for bulk density for different soil types can be substituted, but this is less accurate. Some instruments require a soil-specific calibration (see Note 7.4.1).

Second, the density of water must be close to 1 g/cm³. High concentrations of dissolved substances, e.g. salts, change the density of water significantly. Consequently, volumetric water content measured in saline and salt-affected soils may be inaccurate. Given these troubles, why calculate volumetric water content at all?

There are several important reasons. First, volumetric water content expresses the true percentage of the soil's volume occupied by the substance, H_2O:

$$\text{Volumetric water percentage}, P_v = \theta_v \times 100$$

Because the density of soil varies in the landscape, its unit weight is not constant. Therefore, to compare the true water content in different soils, "apples to apples" as they say, a volumetric measure conditioned on dry density per Eq. 2 is needed.

Second, plants depend on water extracted from a volume of soil. Calculating water content on a volume basis is more useful in agricultural water management. Volumetric water content is also needed to calculate the reservoir of water in the soil; the depth of water needed to wet that soil by irrigation or rainfall; and the *degree of saturation*. The degree of saturation (symbol: S) aka 'water-filled pore space' is the ratio of water volume present *relative to the soil pore volume* or porosity[2]. In contrast, volumetric water content θ_v, or 'volume wetness', is the ratio of water present *relative to the soil volume*. Degree of saturation ranges from 0% in a completely dry soil to 100% in a saturated soil assuming no air is present. In contrast, volumetric water content at saturation ranges from around 40% (sandy soil) to 60% (clayey soil) but can never reach 100%.

Third, field ***water balance*** studies use volumetric water content because converting to depth of water or reservoir of water is straightforward when compared to the whole soil volume as shown following Example 2.

Example 2 The same investigator in Example 1 employed a cylindrical tool with volume 1,000 cm³ to collect the sample. A dry bulk density 1.45 g/cm³ was determined per Equation 3. What is the volumetric water content?

Volumetric water content is calculated as:

$$\theta_v = \theta_g \times \frac{\rho_b}{\rho_w}$$

$$\theta_v = \frac{250g}{1{,}450g} \times \frac{1.45g/cm^3}{1g/cm^3} = \frac{0.25\ cm^3}{cm^3}$$

The volumetric water percentage, $P_v = \theta_v \times 100 = 25\%$

In other words, the *true* fraction of soil volume occupied by water is 25%. Compare this to the mass water content 17.2%. Mass water content P_m is not a true fractional value because the denominator is not the whole (soil + water) sample volume, just the oven-dried fraction. Volumetric water content also tells us that in each centimeter depth of soil, there is 0.25 cm water. So, the total reserve of water in the 15 cm soil layer is 0.25 × 10 cm = 2.5 cm deep (1").

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[2] Porosity is the volume fraction of nonsolid space whether air- or water-filled. See Technical Note 2 Section 2.3 for details and sample calculations.

It also means that the amount of irrigation water needed to wet a dry soil layer 10 cm deep to 25% is 2.5 cm. What is the rationale for this?

Consider a 1 cm cube of soil with 25% volumetric water content. If all the solid particles were removed, leaving only water, the water would occupy a layer 1 × 1 × 0.25 cm (**Figure 7.4.3**). If we sprinkled 0.25 cm^3 of water on the cube, and the soil in the cube was oven-dry to begin with, the water would eventually diffuse through the cube such that its volumetric water content would reach 0.25 cm^3/cm^3. The value of θ_v would, therefore, also be the *equivalent depth* of water as if it were natural precipitation or irrigation water. Furthermore, the equivalent depth of water would be related directly to the *volume of water per unit land area*, and the equivalent depth of water in a *soil layer*.

Recast in two dimensions, the depth of water and solid particles in typical agricultural soil might look something like **Figure 7.4.4**. We'll define the categories gravitational, plant available, and unavailable water in **Figure 7.4.4** in Part III of this Technical Note but for now the important point to convey is that they, too, are fractional values of equivalent depth that characterize the three-dimensional network of soil pores. It is also important to note that volumetric units are length cubed, or $L \times L \times L$ where L can be any measured length, not just centimeters. The system of units is important when comparing values or doing mathematical operations. Don't mix up your units!

Comparing the data in **Table 7.4.1**, the soil in Example 2 might be classified as medium-textured at ***field capacity*** (capillary pores filled with water). Or it might be a heavy-textured soil close to the ***permanent wilting point***. We cannot tell. This ambiguity exposes a fundamental flaw concerning volumetric water content: it is not sufficient to describe the degree of wetness or dryness of a soil with respect to the range of water content plants are most comfortable growing in. We need to define another property of soil water, one that permits the determination of how hard the plant must work to extract a unit amount. This property is ***water potential***, which specifies the energy status of water.

The concept of water existing in a 'potential' state is rooted in classical physics describing the interrelations of motion, energy, and force. The good news is: you don't need a Ph.D. in physics to apply water potential in practice. Water potential can, on a practical level, be compared to reading a thermometer, a simple tool everyone is familiar with (**Figure 7.4.5**).

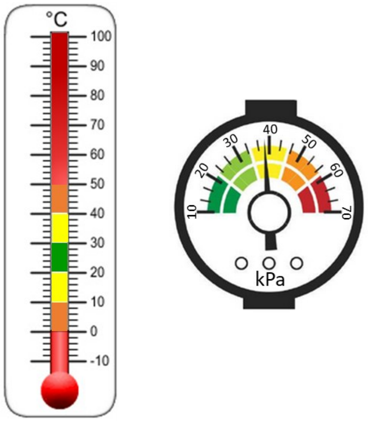

Figure 7.4.5 Left: thermometer measuring heat content in degrees Celsius with fill color indicating human comfort ranges. Right: dial gauge measuring water potential in kilopascals (kPa) with fill color indicating plant comfort ranges.

Green=optimal

Red= danger zone.

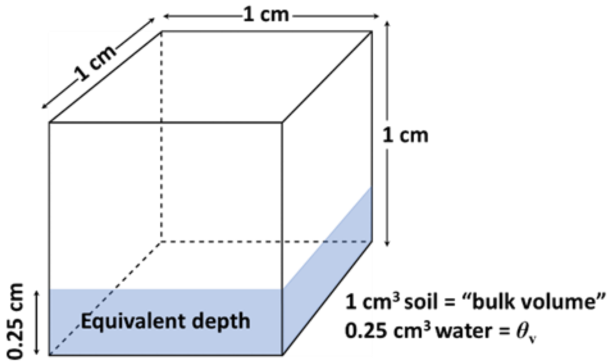

Figure 7.4.3 Display of volumetric water content as an equivalent depth of water. The cube has a bulk volume of 1 cm^3 and volumetric water content 0.25 cm^3. Because the cross-sectional area is the same for both water volume and bulk volume, units of depth may be used to describe volumetric measurements. The equivalent depth of water relates directly to the volume of water per unit soil layer depth and per unit land area.

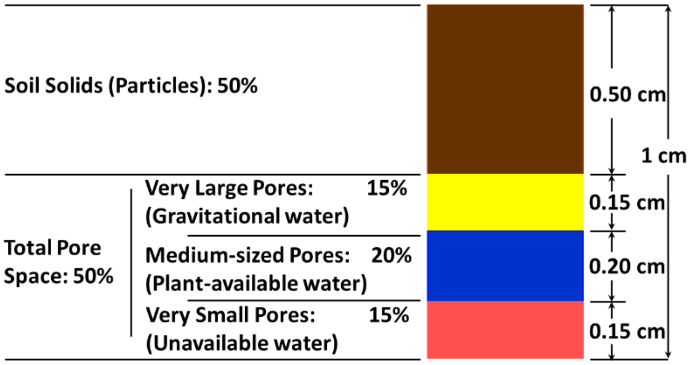

Figure 7.4.4 Volumetric water content as an equivalent depth of water in two dimensions. Fractional values for soil solids and the various pore sizes approximate those of a typical agricultural soil. *Adapted from McCarty et al. 2016.*

Table 7.4.1 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.

A thermometer measures heat content (analogous to water content) in temperature units. We don't need to master the physics of heat transfer to adjust the comfort level in a room (dial the thermostat!). Similarly, water potential tells how comfortable plants are under the current soil water regime. Water potential can tell when it's time to add water, but not how much. That's where volumetric water content comes into play. Nevertheless, a full physical description of water potential is invaluable and certainly not beyond the grasp of the average dirt hog.

First, let's go back to school for a refresher.

In classical physics two principal forms of energy are recognized: kinetic and potential. Soil water, like other natural bodies, can possess energy in different quantities and forms. Surface water can move quite rapidly and its kinetic energy, which is proportional to velocity squared, is sometimes felt with deadly impact: witness captured footage from the 2011 tsunami in Japan. The kinetic energy of water may also be harnessed to help operate machinery like water wheels that generate electricity. On the other hand, soil water moves slow enough so its kinetic energy is often ignored. In contrast, potential energy, which is due to position or internal conditions, is a significant and measurable quantity telling us directly if a body of water has motive force, and if so, its direction. Careful experiments by Julius Sachs in the late 19th century demonstrated that plants absorb water from the soil and that water is exchanged in the process. How, then, does a body of water acquire the property of motion?

Water molecules diffused in the soil matrix are subject to a variety of forces that tend to either accelerate or retard their motion. A ***force*** may be understood as the action of one body upon another that tends to produce motion, changes the rate of motion, or changes direction. A familiar example is gravity: the tendency of a body that has mass to gravitate toward another body with mass. On Earth, the force of gravity gives a body weight and draws it to its center. Thus, a feather in Earth's gravitational field exhibits a descending motion proportional to its mass times an acceleration factor. This relationship is summarized by Newton's famous Second Law:

$$F = ma$$

where m is equal to the mass of a body, and a is equal to the acceleration of that body under the influence of Earth's gravitational field. At sea level the acceleration due to gravity is 9.81 m/s^2, symbolized by the letter g.

Work is defined as the action of a force through a distance, without regard to time (**Figure 7.4.6**). Work may be calculated by multiplying the force times the distance through which the force acts, or:

$$\text{Work} = \text{force x distance}$$

For example, if a load requires 10 kilograms of force to move it vertically a distance of three meters, the quantity of work done is 10 kilograms x 3 meters, or 30-kilogram force meters (kgf • m) or 294.20 Newton meters (N•m). Likewise, a quantity of work, called *free energy*, must be exchanged to remove water molecules in the soil from their present state to a reference state of free, pure water, and elevation defined to be zero. The greater the quantity of free energy water molecules contain, the greater their ability to do work, and vice-versa. Determining the relative free energy of a body of water in different regions would allow us to evaluate the forces acting in all directions and determine how much work is required to remove it. This free energy is known as ***water potential***, symbolized by the Greek letter psi Ψ.

The primary sources of free energy driving water movement in the soil are *gravitational*, *osmotic*, *matric*, and *pressure* (hydrostatic) potential. These component forces act simultaneously and contribute to the total soil water potential as:

$$\Psi_{total} = \Psi_g + \Psi_o + \Psi_p + \Psi_m$$

where

Ψ_g = gravitational potential

Ψ_o = osmotic potential

Ψ_p = pressure potential

Ψ_m = matric potential

Because the components overlap in effect, they are not, strictly speaking, additive. However, the above expression conveniently relates the idea of component parts in the evaluation of total water potential. This should be kept in mind when interpreting water potential readings where more than one component is active.

Water potential has dimensions of energy per unit quantity of water. Energy units are those of the ***Joule*** (symbol: J), while the dimensions of water quantity depend on the way it is expressed. Some possible choices are:

> <u>Energy per unit mass of water</u> (J/kg)
>
> This adheres to thermodynamic dimensions but is not widely used in practice.
>
> <u>Energy per unit volume of water</u> (pressure) (J/m^3 or J/N^2 = Joules per ***Newton*** squared)
>
> This is the most common expression of water potential and is dimensionally equivalent to pressure units like the Pascal, bar, atmosphere. Pressure units are interconvertible with Imperial pounds per square inch (PSI).
>
> <u>Energy per unit weight of water</u> (density) J/N = m
>
> This is also commonly used and has dimensions of length (meter, m) referred to as *head*. The density of a liquid column of water (or mercury) is specified at different temperatures like 0° C, 4° C, 24°C, and so on.

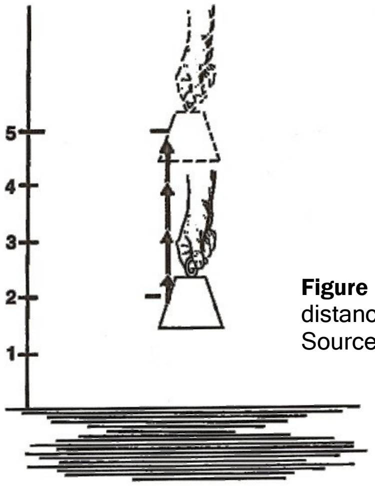

Figure 7.4.6 Work equals force x distance without a time factor. Source: *Finner and Straub, 1985.*

The following unit conversions are noted:

1 bar = 100 J/kg

1 bar = 100,000 pascals =14.5 psi

1 bar = 10 m column of water @ 4 °C

The prevailing metric unit of pressure is the kilopascal (abbreviated kPa), which corresponds to one thousand (10^3) pascals. Other combinations like hectopascal (hPa, 10^2 pascals) and megapascal (MPa, 10^6 pascals) are possible. Unless noted, the kilopascal or megapascal are used hereafter and in subsequent Technical Notes as the unit quantity of water potential.

Now that we've sketched the basic outline of water potential, let's describe each component in detail.

Gravitational potential (symbolized by Ψ_g: Greek letter psi subscripted by letter g), describes the pull of gravity on water depending on its position in Earth's gravitational field. At any point, the energy contained in Ψ_g depends solely on its elevation relative to a reference plane. This can be expressed in mathematical notation as:

$$\Psi_g = gh$$

where g is the acceleration due to gravity, 9.81 m/s², from Newton's second law, and h is the height of water above a reference plane (**Figure 7.4.7**). For this reason, water spontaneously runs downhill "seeking its own level" whereas work is required to remove it uphill. The reference plane is arbitrarily located at some lower boundary so that Ψ_g above the reference level is always positive. However, Ψ_g can assume positive or negative values depending on whether the water is above (+) or below (-) the reference plane. If the soil surface is taken as the reference plane, then points below this elevation are always more negative with respect to the surface even though the water is classified as 'gravitational' (see Technical Note 7 Part III for more on this).

Gravitational potential is not affected by the chemical nature or pressure conditions of the water, nor of soil properties per se. As such, we can't measure Ψ_g on a soil sample in the laboratory; Ψ_g exists solely as a field phenomenon where it plays an important role in removing excess water from the soil root zone. After free drainage ceases in a wetted soil, gravitational forces may still propel water downward until retarding forces begin to counter downward movement in a balancing act destined to end in a stalemate where the movement of water essentially reaches equilibrium, i.e. no further descent occurs. The retarding forces originate from capillarity, an important phenomenon discussed further down in this Technical Note.

Osmotic potential (symbol: Ψ_o) is created by the presence of dissolved substances in the soil solution. These may be inorganic salts or organic compounds, but they share the attribute of having a net positive or negative charge. Recall from Technical Note 7 Part I that water is a polar molecule (bipolar, to be precise). When solutes (dissolved substances) are mingled with water the force of attraction between the solutes and water gives the water molecules less freedom to move, thus reducing the potential energy of the water. Water molecules will migrate to the area of higher solute concentration (lower energy) in the process of *osmosis* (**Figure 7.4.8**).

Solute potential is always negative. Dissolved inorganic ions like sodium (Na^+), calcium (Ca^{+2}), magnesium (Mg^{+2}), ammonium (NH_4^+) nitrate (NO_3^-), and chloride (Cl^-) and organic bicarbonates (HCO_3-$^-$), whether naturally occurring or from fertilizer or irrigation water, all contribute to osmotic potential. Normally the osmotic potential of soil water is

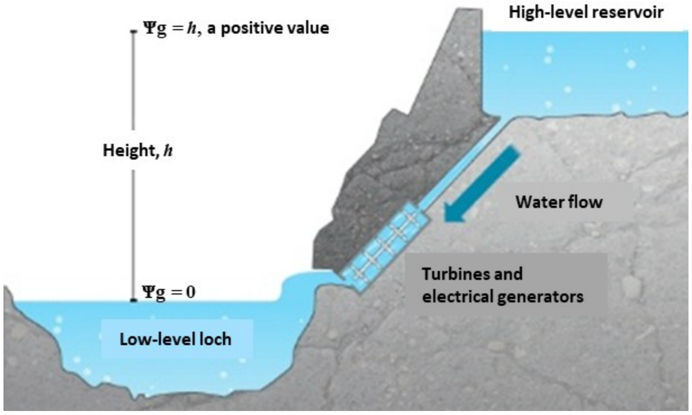

Figure 7.4.7 Gravitational potential, Ψg, is the energy of water that is potentially available to be released when water moves from a high position to a lower position. Energy is proportional to the height above a reference plane where $\Psi g = 0$. Gravitational potential plays an important role in removing excess water from the soil root zone. *Source: adapted from Meter Group.*

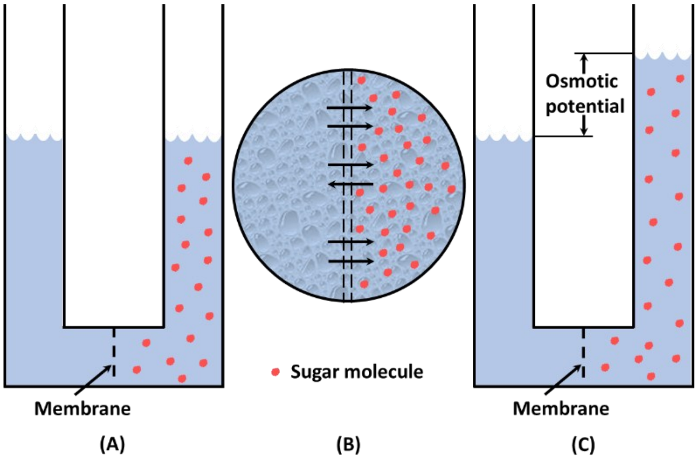

Figure 7.4.8 Illustration of the process of osmosis and the creation of osmotic potential. The U-tube in (A) is filled with water and the two arms separated by a membrane that is permeable to water molecules but not dissolved sugar. The close-up view in (B) shows how the water molecules migrate across the membrane in both directions whereas the sugar does not. Because sugar lowers the energy state of water, more molecules will migrate from left to right than vice-versa. This causes the height of the solution in the right arm (C) to rise above the level in the left arm. The difference in height of the water levels is measured as osmotic potential.

negligible because nutrient concentrations are low. Typical values might be -0.01 MPa. However, Ψ_o in soils with a high concentration of salts may be much lower.

Fertilizer 'burn' is a classic (and all too common) example of low osmotic potential created by placing soluble fertilizer salts like nitrogen and potassium too near the root zone. Because plant roots act as a semi-permeable membrane, the high concentration of salts on the outside prevent water movement into the plant and may even pull water out. The characteristic symptoms of fertilizer burn are tissue desiccation and death (**Figure 7.4.9**). In the reverse process, work is required to remove solutes from water, that is, bring it back to a standard pure state (reverse osmosis: RO).

Figure 7.4.9 Leaf scorch symptoms in corn caused by placement of fertilizer salts near the plant.

Inset: Corn root radicle damaged by anhydrous ammonia application. Tissue damage may be caused by excess soluble salts (osmotic effect) *and* free ammonia which is directly toxic.

Pressure potential (symbol: Ψ_p) is related to positive hydrostatic forces arising from the weight of overhead water in a saturated soil or aquifer, the overburden of soil and rock, the presence of gases, or a combination. Pressure potential is always zero above the water table in the unsaturated zone, and positive below the water table. Positive pressure potential, or 'hydraulic' or 'pressure head' in engineering jargon, results whenever fluid water has a hydrostatic pressure *greater than* atmospheric (1 atmosphere or 101.3 kPa at sea level). Fluid pressure is responsible for the transfer of water, whether in a pipe, conduit, or underground. Water movement via pressure potential may be modified by gravitational and ***matric potential*** (symbol: Ψ_m) forces. Matric potential is a special case of pressure potential whereby a negative pressure *less than* atmospheric is developed from the adhesion between water and soil mineral-organic particles (adsorption) and capillary forces. Capillary forces are responsible for water being pulled up in a narrow open space in opposition to the force of gravity, and the formation of a *meniscus* (**Figure 7.4.10**). The height to which water will rise in a capillary tube is governed by the *capillary rise equation*:

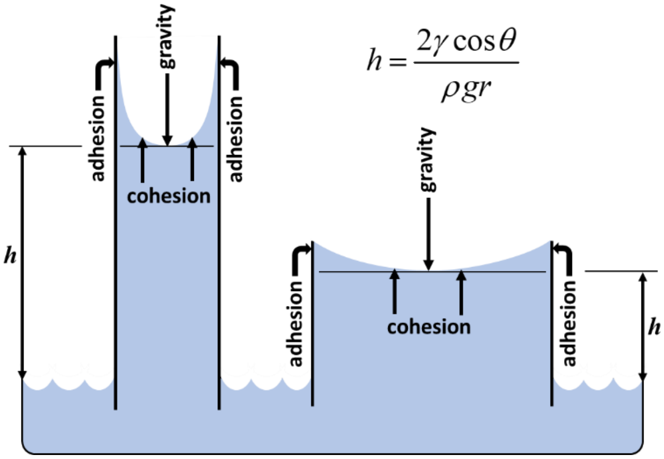

Figure 7.4.10 Illustration of the capillary phenomenon of water rising in a tube of uniform circular cross section. Water rises in the tube to height h by balancing the forces of adhesion, cohesion (surface tension), and gravity according to the capillary rise equation. This creates a vacuum, or apparent suction pulling the water up against the force of gravity. Because this phenomenon can operate in any direction, it is important in considering water retention in soil pores, which are much more complex than the illustration above.

$$h=\frac{2\gamma\cos\theta}{\rho g r} \qquad [\text{Eq. 5}]$$

where:

h is the height[3] the water is lifted in the tube, cm
γ is the coefficient of liquid-air surface tension, dynes/cm
θ is the angle of contact of the water with the surface, deg.
ρ is the density of water, 1 g/cm^3
g is acceleration due to gravity, 980 cm/s^2
r is the radius of the tube, cm

Two things are apparent from Eq. 5. First, there is an inverse relationship between the radius of the tube and the height of the water in the tube, i.e. the smaller the diameter, the higher the rise. Since capillary forces govern the height of water in the tube, the matric potential forces must decrease (i.e., become more negative) as the tube diameter decreases. Second, the force of gravity divides the coefficient of surface tension (for water, γ = 73 dynes/cm). Thus, the curvature of the meniscus is governed by the balance of the forces of gravity and the forces of cohesion in surface tension, which are weak compared to that of adhesion. Water molecules near the middle of the meniscus are held by surface tension because they're too far away from the walls of the tube to be affected by adhesion. Surface tension is therefore the first force to break under the downward pull of gravity and is the limiting factor in capillary rise.

In the soil, water is held in the pore spaces between particles and on the surface of the particles themselves. The positive end of the dipolar water molecule is strongly attracted to the negative charges of clay particles, giving rise

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[3] Many sources fail to mention if h specifies the elevation of the highest part of the meniscus, the lowest part, or some average in between. In Figure 7.4.10, h is measured from the base of the meniscus as if reading the volume in a graduated cylinder or pipette. It can also be defined as the average of the highest and lowest elevations.

to adhesive forces. Collectively, capillary forces are created by the adhesion of water molecules to soil mineral surfaces, cellulose, proteins, etc. and the surface tension of water as explained previously. These forces combine to create a negative pressure potential called ***suction***, or ***tension***, that tends to counter downward gravitational forces in the soil although differences in matric potential from site to site can drive horizontal movement.

If we think of soil pores as a collection of interconnected tubes, Eq. 5 can be applied to determine the movement of water in the soil. Water in ***macropores*** is held mainly by surface tension and the first to break under the pull of gravity. Webster and Becket (1972) found that in temperate regions gravity exerts a matric suction of 5 kPa. This means that capillary menisci are prevented from forming in soil pores wider than 60 µm (micrometers) according to Eq. 5, rearranged and simplified as:

$$r = \frac{0.15}{h}$$

Water in macropores > 60 µm tends to be rapidly pulled downward by gravity, thereby enabling free drainage and air entry in the soil. Water remaining in the network of ***micropores*** <60 µm is attracted to edges of the soil particles by stronger adhesive forces (**Figure 7.4.11**). The region of gravitational drainage may, however, range between 5 kPa and 33 kPa matric suction depending on soil particle shape, packing density, and structure. Water held in the micropore network will also exhibit greater capillary rise according to Eq. 5. The phenomenon of capillary rise of water in the soil micropore network is of primary importance supplying water to plants, particularly under dry conditions when water must be lifted from zones deeper in the soil profile.

The flow of water in unsaturated soil is governed by differences in matric potential and determines entry of a unit amount into plant roots. The rate at which water flows is, in turn, governed by the number, size, shape, and continuity of soil pores. In general, the number of micropores in mineral soils is much greater than that of macropores regardless of pedogenic factors. Unless a barrier prevents it, water will migrate spontaneously toward a network of ever-smaller pores because the force of attraction between water molecules and particle surfaces is strong and energy state minimal in this configuration. **Figure 7.4.12** illustrates how matric potential varies with distance from soil particles. Water located close to soil particles is less free to move about compared to water in the center or near the meniscus. Water in narrow pore channels is held by strong matric forces to a degree where it may be unavailable to plants. Measuring matric potential in the soil root zone is therefore of primary importance in determining the quantity of available plant water and in irrigation scheduling. Instruments devised to measure matric potential in situ include the tensiometer and gypsum block sensor (see Note 7.4.2, Page 9).

Note that it's not the absolute amount of total energy contained in water that itself causes movement, but rather the relative *difference in energy levels* between locations in the soil. The rate of decrease of potential energy across a segment is in fact the moving force causing mass flow. This is called a ***gradient***. We'll call upon gradient frequently in

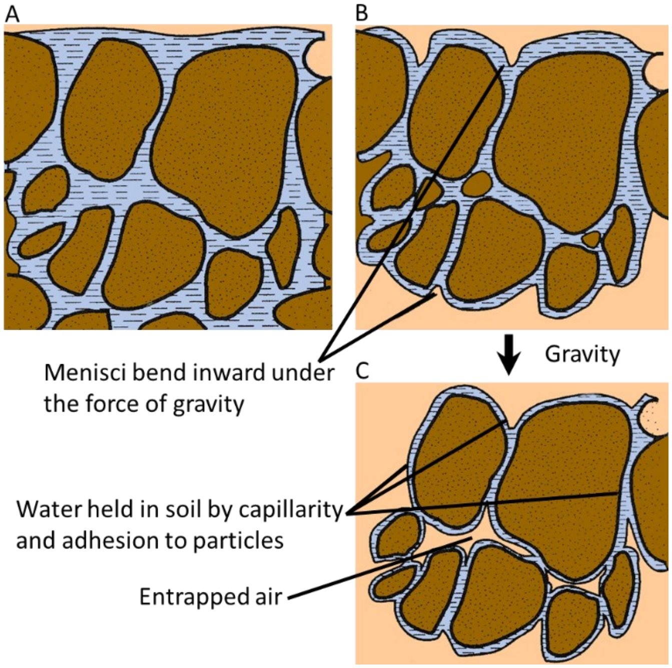


Figure 7.4.11 Three stages of water retention in the soil explained by gravitational and matric potential forces. At saturation (A), menisci are flat and the matric potential zero. As drainage begins (B), gravity bends the menisci inward (B) against the forces of surface tension and adhesion. Finally, 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.

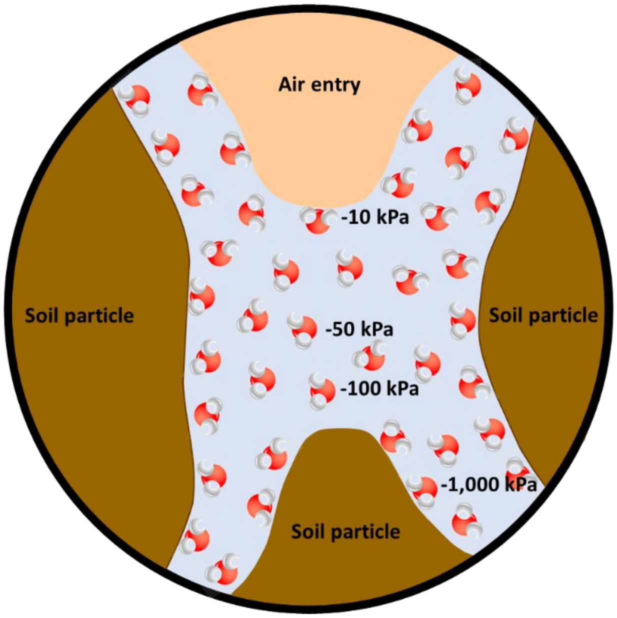


Figure 7.4.12 Cross section of a soil pore and the solid particles comprising the walls, showing how matric potential decreases (becomes more negative) as distance from the particle surfaces increases. Water in the largest pores at the air entry point is held by weak surface tension forces whereas, water in smaller pores is held tightly because they are close to multiple particle surfaces.

this and other Technical Notes so the reader should understand the meaning as well as the context in which the term is used.

Water potential and flow are often compared to Ohm's Law, the equation that relates the three quantities in the transport of electrical current:

$$I = \frac{V}{R}$$

where the electric current I (ampere=coulombs per second) is proportional to the potential difference, V (voltage) and inversely proportional to R, resistance (ohms). Here, potential difference (V) is the driving force (gradient) for the conduction of a quantity of electrical charge (coulombs) in a circuit. In hydraulic systems, instead of coulombs of electrical charge, current is equivalent to the flow of water molecules through or across a segment whereas voltage (pressure) is directly proportional to the water potential difference (free energy) driving flow, symbolized by h in **Figure 7.4.13**. Resistance is a feature of hydraulic systems that divides pressure like Voltage in Ohm's Law, an analogy we'll call upon in Section 7.6 in considering water loss from plants.

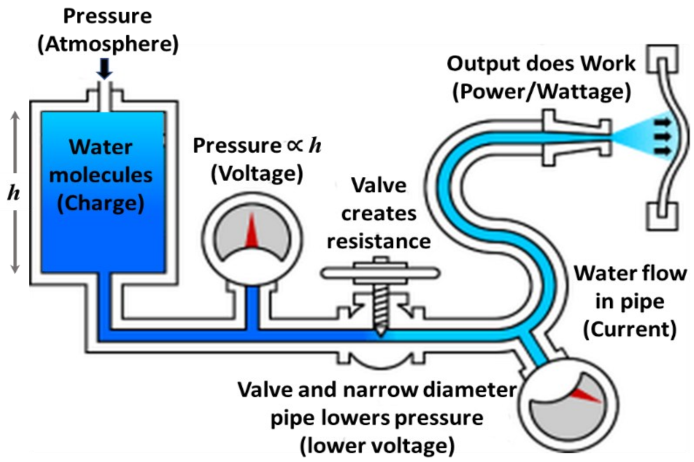


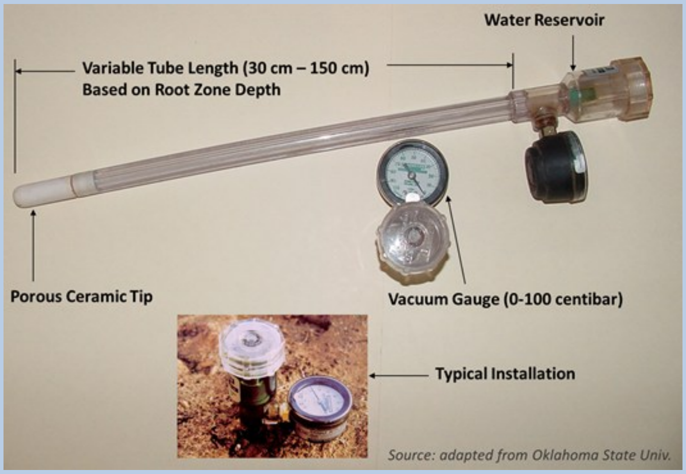
Figure 7.4.13 Illustration of hydraulic-Ohm's Law analogy. Voltage is represented by the potential difference, h (free energy) in a water tank forcing flow through the pipe; water molecules represent electric Charge; Current is water flowing through the pipe: the more pressure there is the more current you get. Valves and piping restrict water flow like a resistor in an electrical circuit, lowering pressure. Power output is the product of Volts (pressure) × Current (flow). *Image source: adapted from Weebly.com*

7.5 Summary

Soil water can be described two ways: (1) water content and (2) water potential. Water content measures the mass of water relative to the mass of oven-dry soil. Various measures of soil water content are derived from mass water content. Water potential describes the state of water by reference to its energy status. It is the *difference in total free energy* that drives water movement in different regions of the soil, ultimately delivering water to the surface of the plant root.

Note 7.4.2

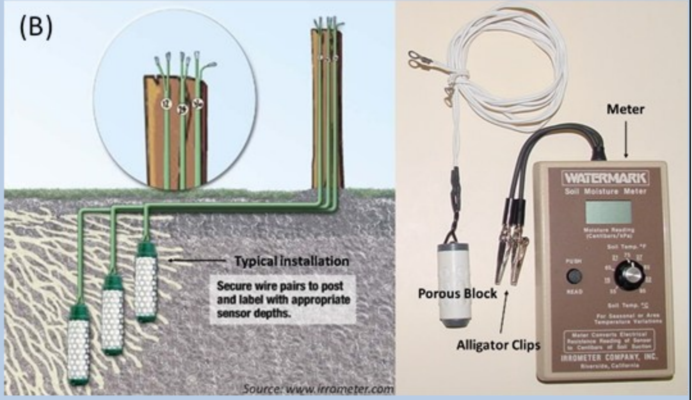
Tensiometers and conductivity sensors are stationary instruments used to determine matric potential at fixed points in the field. Tensiometers are sealed, water-filled tubes with a reservoir and vacuum gauge on the top end and a porous ceramic tip on the bottom end (Inset A).



Source: adapted from Oklahoma State Univ.

Water in the tube comes into equilibrium with water in the soil, providing a direct measure of how much force (i.e. tension or negative pressure) the plant would have to exert to pull water from soil pores. Tension is registered as positive pressure values on the vacuum gauge dial (centibars or kPa). The operating range is about 0-80 which has limitations in medium and fine-textured soils. Tensiometers measure only matric potential. Accuracy: ±2%

Conductivity sensors measure soil matric potential indirectly by applying an alternating current voltage on two electrodes embedded in a block of porous material (typically gypsum) in contact with the soil (Inset B).



Source: www.irrometer.com

As the potential changes with water content, conductivity across two electrodes in the sensor's porous block also changes. Conductivity is measured by a hand-held meter and converted to units of tension (centibars or kPa) via calibration equations. Conductivity sensors work better at higher tensions (lower water content) compared to tensiometers but are affected by fluctuations in soil temperature. Accuracy: ±20%

Readings from both instruments are qualitative in nature as they do not measure the quantity of water in the soil. They are widely used for irrigation timing but cannot prescribe the amount to irrigate. Several recent models come equipped with electronic pressure transducers suitable for interfacing with dataloggers and wireless communication services.

Water in unsaturated soil is under tension, i.e. its potential energy state is negative, therefore a drop of water at any potential above zero will be drawn into the soil by the combined suction of capillary and adhesive forces. Matric forces are largely responsible for the movement of water in unsaturated soil. Matric potential in the soil root zone can be measured by stationary sensors, which are indispensable for agricultural water management.

In the next Section, we'll look at how water moves into, and out of, the plant, and what happens on the journey between.

7.6 HOW PLANTS GET (AND LOSE) THEIR WATER

Water is absorbed into the plant primarily at the root tip, especially the area surrounding the root hairs. This process requires water to flow radially across a segment of cortex tissue cells between the root epidermis and endodermis before it reaches the conductive tissue known as xylem (**Figure 7.6.1**). Xylem vessels are interconnected tubes that form a continuous vascular pipeline transporting water from the roots to the shoots.

Water may travel through the root cortex in the following pathways:

- apoplastic pathway
- symplastic pathway
- transmembrane pathway

Water conducted through the ***apoplast*** flows between cells, along cell walls or through intercellular air spaces. Water conducted via the ***symplast*** flows through the cytoplastic connecting strands or *plasmodesmata* without crossing the plasma membrane. In the transmembrane pathway, water flows across the plasma membrane. Because water conducted in the apoplast and symplast does not cross any semipermeable membrane, the driving force for mass flow of water traveling across the root cortex is just the hydrostatic pressure gradient, including capillary forces arising from intercellular free space. In contrast, water emptying into the xylem tissue must cross the cell membrane. Here, the relevant driving force is total water potential, including osmotic potential created by the concentration of solutes.

The reader should note in **Figure 7.6.1** the apoplastic pathway is blocked at the endodermis by an impermeable band of cell walls called the ***Casparian strip***. The Casparian strip breaks continuity with the apoplast, forcing all water and dissolved substances therein, to cross the endodermis through the symplastic pathway.[4] This ensures that plants can selectively filter the composition of solutes passing through to the xylem. Once water reaches the xylem vessels, it can move in a continuous stream with very little resistance. But what is the force driving this column?

In Section 7.4 we learned that water tends to flow spontaneously from an area of high potential to an area of low potential. Therefore, water potential inside the plant root must be lower than the surrounding soil:

$$\Psi_{root} < \Psi_{soil}$$

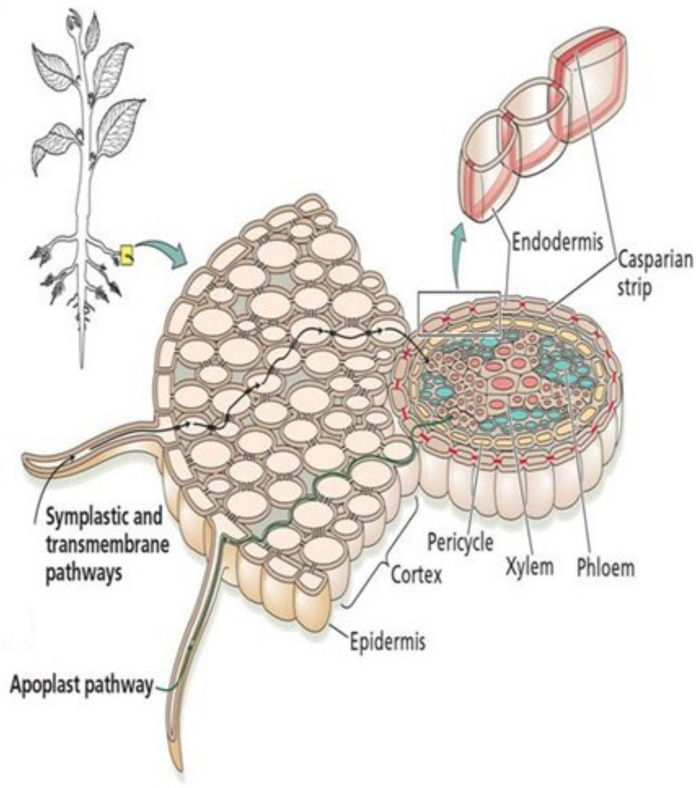


Figure 7.6.1 Possible pathways for water uptake by plant roots: apoplastic, symplastic and transmembrane. At the endodermis, flow through the apoplastic free space is blocked by the Casparian strip, forcing water and solutes into the symplastic pathway and eventually across the cell membrane. Because permeability of the cell membrane depends on respiration, water and solute uptake are affected by temperature and oxygen level in the soil. Thus, in poorly drained and waterlogged soil, plants suffer from water deficiency, showing symptoms of wilting as if drought-stricken even though the soil's water supply is brimming. *Source: adapted from Taiz and Zeigler 2006.*

And *total* water potential must decline from the bulk soil to the surface of the root otherwise no flow, and hence entry of water, is possible.

Similarly, the mechanism driving the transport of liquid water in the xylem tissue is a water potential gradient established by the transpirational loss of water from the leaves to the atmosphere. Water molecules in the xylem vessels are bound to each other with the help of hydrogen bonds, the same bonds that impart cohesion to free liquid water. When water molecules reach the surface of the leaves they evaporate through openings called *stomata* that expose the vascular system of plants to the atmosphere and thus, a sink of extremely low water potential which, in turn, exerts a very strong suction on the water stream in the entire plant. The continuous evaporation of water dilutes liquid water (i.e., increases solute concentration) leading to a decrease in osmotic potential, which contributes to creating more steepness in the water-potential gradient between the soil and plant.

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[4] On the tips of very young plant roots the Casparian strip may be undeveloped. In this region the apoplastic pathway is of major importance in the uptake and transport of calcium (Ca^{2+}) and magnesium (Mg^{2+}).

The entire column of water stretching from the soil to the root and extending through the xylem to the upper reaches of the plant canopy where it ultimately escapes back to the atmosphere is thus driven by a water potential gradient across the soil-plant-atmosphere continuum (SPAC) depicted in **Figure 7.6.2.** This energy gradient can be written as

$$\Psi_{atmosphere} < \Psi_{leaf} < \Psi_{stem} < \Psi_{root} < \Psi_{soil}$$

where Ψ denotes water potential. In the soil, water potential may range anywhere from saturation (Ψ=0) to the permanent wilting point (Ψ=1.5 MPa) or even drop below the wilting point when drying is extreme. But generally, water potential in the atmosphere is orders of magnitude lower ($\Psi \leq 100$ MPa) so there will be a difference between soil and atmosphere with plants acting as water conductors in-between.

Unlike nutrient uptake which is activated by metabolism, the entire process of water uptake by plants is passive in that it does not rely on the expenditure of energy[5]. It follows the simple rule that water flows spontaneously *from a region of higher potential to a region of lower potential* just as in the case of water flow in the soil.

Still, the reservoir of soil water is not inexhaustible. As the soil dries, Ψ_{soil} (which is usually dominated by Ψ_m near the surface) steadily increases. In dense field plantings, for example, Ψ_{soil} in the vicinity of the roots can reach -0.5 Mpa or less even though water potential away from the roots is at field capacity, ~0.03 MPa. When water potential outside the vicinity of the root is lower than inside the root, i.e.

$$\Psi_{soil} < \Psi_{root}$$

the flow of water will stop unless the plant adjusts Ψ_{root}. Plants can, to a certain extent, adjust internal osmotic potential to maintain a continuous stream of water. A more efficient solution, from the plant's perspective, is to regulate the loss of water via transpiration so it matches uptake from the soil.

Land plants have evolved several mechanisms to limit water loss: (1) closing stomatal pores in response to water deficit in the leaf; and (2) fortifying anatomical features like the leaf cuticle, epidermal cells, and specialized hair-like structures called *trichomes*.

Regulation of transpiration is achieved primary through opening and closing of stomata, which are microscopic pores on the leaf surface (**Figure 7.6.3**). Stomata are surrounded by two specialized guard cells that dynamically adjust their turgor pressure in response to environmental cues like light intensity and quality, leaf water status, and carbon dioxide concentrations. Photosynthesis depends on the free exchange of oxygen and CO_2 between the leaf and atmosphere, so stomatal pores must stay open, at least part of the time[6].

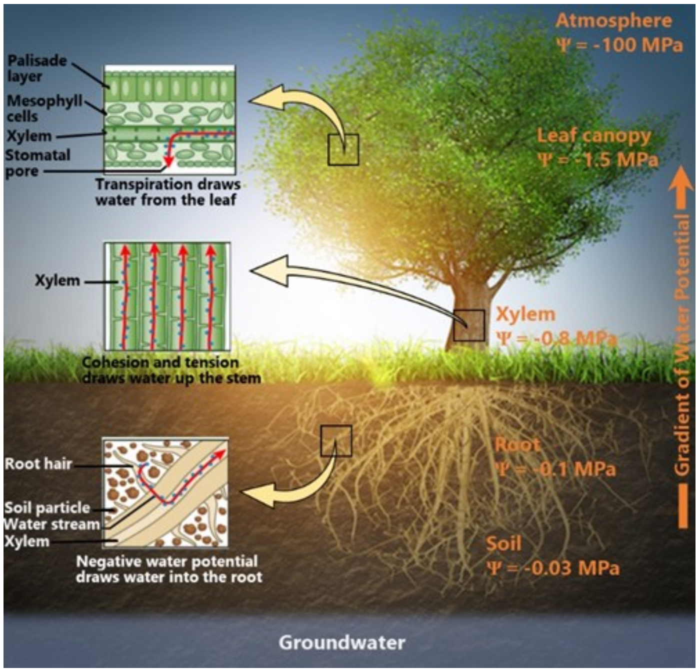

Figure 7.6.2 Continuum of water movement down a potential gradient in the soil-plant-atmosphere system. Water potential values, denoted by Ψ, are in megapascals. The water potential gradient in **Figure 7.6.2** is typical at midday on a mild, sunny day with soil near field capacity in a humid to sub-humid region. *Insets credit: adapted from OpenStax Biology.*

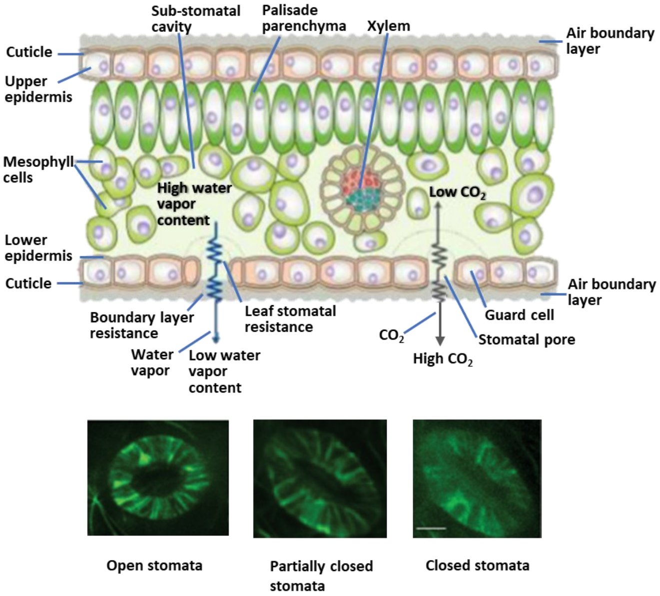

Figure 7.6.3 Illustration of leaf-gas exchange control by the opening and closing of leaf stomatal pores. Water vapor moves from an area of saturation inside the mesophyll cavity to an area of low vapor pressure in the atmosphere. As the stomatal pore closes, leaf stomatal resistance, denoted by resistor symbols in the drawing above, also increases thus regulating the velocity of water vapor exchange. When the stomatal pore is closed, the exchange of water vapor and CO_2 gas is prevented. *Drawing source: adapted from Tiaz and Zeigler 2006; stomatal images: Khanna et al. 2014. https://www.sciencedirect.com/science/article/pii/S1674205214609473*

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[5] While water transport across the cell membrane requires no expenditure of energy per se, any disruption of cell membrane integrity will effectively restrict the flow of water.

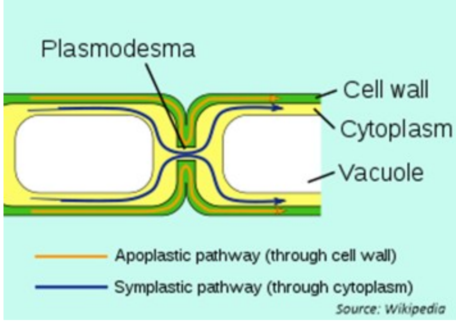
[6] Stomata normally stay open during the daytime and close at night. Because the light reaction in photosynthesis is not occurring at night, there is less benefit from exchanging CO_2 and O_2. This pause allows plants to conserve water while minimizing its impact on photosynthesis.

When stomatal pores begin to close in response to water deficit in the leaf, resistance across the stomatal aperture increases. In turn, the velocity of water vapor, oxygen, and CO_2 exchange decreases. While this automatically cuts down on water loss it also inhibits photosynthesis.

Looking ahead, the imperative for sustainable improvements in food yield will rest upon creating a field environment where the plant's photosynthetic machinery hums along unhindered and Ψ_{soil} is maintained in a favorable range at all times during the growing season. In Part III of this Technical Note, we'll relate soil water content to water potential and determine the optimal range for field crops.

CORE INTELLIGENCE

Apoplast: Transport pathway in vascular plants composed of the network of interconnected cell walls, and any voids (intercellular spaces) between cell walls. The apoplast is a short-distance, nonliving, water- and solute-transport pathway. The cell cuticle and xylem vessels are nonliving and in intimate contact with the apoplast but are not considered part of the apoplast. Compare ***symplast***.



Source: Wikipedia

Bulk Density: Bulk density, abbreviated ρ_b, is defined as the ratio of a mass (M_s) of given soil sample to its bulk volume (V_t):

$$\rho_b = \frac{M_s}{V_t}$$

Bulk density is computed on a wet or dry basis depending on application. For dry bulk density, the mass is determined by drying the sample to a constant weight at 105°C, and the bulk volume is the total volume of soil particles plus pore space at the time of sampling. Common units for bulk density are kg/m^3 (MKS, metric), which is numerically the same as g/cm^3 (CGS, metric); and lbs/ft^3 (English). Dry bulk density is a commonly measured soil physical property required for: 1) determining the degree of compaction and hence as an indicator of soil structural stability; 2) evaluating soil aeration or wetness status (together with soil water content); and 3) converting soil water content and nutrient values from the gravimetric (mass) to the volumetric basis.

Casparian Strip: A band material in the cell walls of the endodermis that is filled with wax-like, hydrophobic material called *suberin.* The Casparian strip serves as a barrier separating the apoplast of the root cortex from the water conducting tissue (xylem) in the central cylinder thereby blocking passage of material between the two. Water and solutes are thereby forced to pass through the plasma membrane via the symplastic pathway in order to cross the endodermis layer.

Dilatancy: The tendency of a granular material to dilate, or increase in volume, when subjected to shear deformation. Dilatancy is a common feature of soils and sands. Because silts and clays both consist of very small particles, they are hard to distinguish visually in the field. Dilatancy is a qualitative test where a small sample of soil is wetted and shaken in the hand to determine the relative amounts of silt and clay constituents. The time it takes for water to rise to the surface and give a shiny or glistening appearance is used to classify the soil. The reaction is explained here. Note: in chemical engineering, dilatancy is a property of fluids whose viscosity increases with shear deformation.

Field Capacity: The amount of water remaining in the soil after free drainage. 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.

Force: Physical quantity defined as the action of one body upon another that tends to produce motion, change the rate of motion, or the direction of motion. Force is measured in newtons (N, metric units) or pounds force (lbf, English units). The metric base units are 1 kg • m/s^2 derived from Newton's second law equation Force (F) = mass (m) • acceleration (a). Seconds are squared (s^2) because acceleration is calculated by dividing change in velocity (meters per second), by time (also measured in seconds).

Gravimetric: a method of quantitative chemical analysis in which two or more constituents in a substance are separated from the sample and weighed to determine their mass or concentration. For example, the mass of water in a soil sample is determined by drying to 105°C until no further change in mass is detected. The quantity of water so determined is called *gravimetric water content*.

Gravitational potential (Ψ_g): The energy stored in water due to its position in relation to a reference plane (positive above the plane, negative below the plane). Gravitational potential is equal to the force of gravity pulling water toward the Earth's center, e.g.

$$\Psi_g = gh$$

where h is the height above or below a reference plane, and g is the gravitational constant 9.81 m/s^2. Conversely, gravitational potential is equal to the work needed to raise a body of water against Earth's gravitational pull from a reference plane.

Gradient: In physics, an increase or decrease in the magnitude of a property (e.g. temperature, pressure, or concentration) observed in passing from one point or moment to another. Gradients can be positive or negative depending on the location of the reference plane.

In situ (adverb); in-situ (adjective): Latin for "in place". Used in many different contexts to describe where an event took place. The phrase can mean "in field", "on site", "in position" as compared to a laboratory or other artificial place.

Joule *(symbol:* ***J****):* unit of work or energy in the International System of Units (SI); it is equal to the work done by a force of one *newton* acting through one meter. Named after the English physicist James Prescott Joule, it equals approximately 0.7377 foot-pounds.

Macropores: Large noncapillary pores that tend to spontaneously drain under the pull of gravity and provide soil aeration. The effective pore diameter is defined as >60 µm (micrometers) based off the assumption that gravity exerts a matric suction of 5 kPa.

Mass: The amount of matter in a body that causes it to have weight in a gravitational field. Mass and weight are not the same properties (compare ***weight***). The unit of measure for mass is the gram or kilogram (metric units).

Matric potential (Ψ_m): An indication of the energy needed to remove water from soil particles, cellulose, proteins, or from within fine capillary pores. Matric potential is always expressed as a negative value indicating the pressure is below that of pure, free water and hence exerts a pulling or suction force. Matric potential is responsible for the soil's water holding capacity and determines the availability of water to plants. Matric potential can be measured directly by instruments like the tensiometer, and gypsum and granular block sensors. Since matric potential varies inversely with soil water content, high tension (i.e. more negative MP values) indicates low soil moisture and vice-versa. The relationship between the matric potential in a substance and its water content is called the *moisture characteristic* (see Technical Note III).

Micropores: Small capillary pores that hold water against the pull of gravity and are responsible for the soil's water holding capacity. The effective pore diameter is defined as < 60 µm.

Newton (*symbol:* ***N***)*;* unit of force in the International System of Units (SI, metric); It is defined as that force necessary to provide a mass of one kilogram with an acceleration of one meter per second per second: 1 kg• m/s^2.

Osmotic potential: Component of water potential that arises in consequence of solutes dissolved in water separated by a semipermeable membrane in plant or animal cells. Osmotic potential is always negative.

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. For many crops, the PWP corresponds closely to a matric water potential of −1.5 MPa.

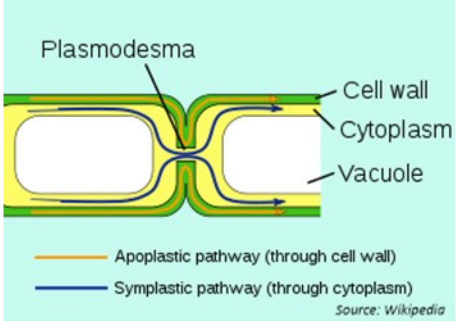
Plasticity: The ability of the fine-grained portion of a soil to change shape, but not volume, under the influence of constant pressure and to retain the impressed shape when the pressure is removed (FAO, 2006). The degree of plasticity, or ***consistence***, depends on water content which, in turn, provides an index of the clay content of a soil. Field tests for soil classification involve rolling a moist sample with the fingers. If a ribbon can be formed and re-formed, the soil material is plastic (clayey); if the ribbon breaks and cannot be re-formed, the material is non-plastic (silty or sandy). The boundaries between liquid and plastic states are described by the Atterberg limits or plasticity index, named for the Swedish chemist and agricultural scientist Albert Atterberg who first defined the limits of soil consistency in 1911.

Pressure potential: The energy stored in water due to hydrostatic forces arising from the weight of overhead water in a saturated soil or aquifer, the overburden of soil and rock, the presence of gases, or a combination. Pressure potential is always zero above the water table in the unsaturated zone, and positive below the water table. Matric potential is a special case of pressure potential whereby a negative pressure less than atmospheric develops from the adhesion between water and soil mineral-organic particles (adsorption) and capillary forces.

Strength: The degree of resistance of a soil mass to crushing or deformation when a force is applied. Strength, along with friability, plasticity, stickiness, are properties of soil *consistence* (see ***plasticity***). Soil strength is determined by the degree of cohesion and internal friction existing between soil particles. Units are pounds force/ft^2 (English) and Newton/m^2 (metric). Soil strength may be determined qualitatively from the pressure required to squeeze a fragment of air-dry soil between the fingers. Terms such as brittle (fails suddenly with little strain), elastic (rubbery), friable (crumbles easily), and loose (non-coherent) are commonly used to describe soil strength.

Suction: Absolute value of matric potential and a positive number. Reserving a separate term for the absolute value is endorsed for two reasons: (1) it allows for the expression of a negative number in terms of a positive pressure head, h; (2) it allows for the use of logarithms to plot numerical values spanning orders of magnitude. In practice, a matric potential of -100 kPa would be written 100 kPa matric suction or 1,000 cm H_20 matric suction *head* (see also ***tension***).

Symplast: Cell-to-cell transport pathway in vascular plants composed of the network of cytoplasmic connecting strands, the plasmodesmata. The symplast is a short-distance, living, water- and solute-transport pathway. The symplast is not considered part of the living phloem conduits and their companion cells, which are involved in long-distance transport. Compare ***apoplast***.



Source: Wikipedia

Tension: Absolute value of matric potential and a positive number. Tension and suction are used interchangeably. See ***suction***.

Water balance: The quantitative evaluation of water additions and subtractions in the near-surface and soil root zone. Evapotranspiration (ET) and drainage account for the biggest subtractions whereas precipitation and irrigation provide the major additions. Crop water use for cellular growth is a minute fraction (usually < 1%) of transpiration and is usually disregarded. Runoff, run-on, capillary and water table rise are accounted for where they occur.

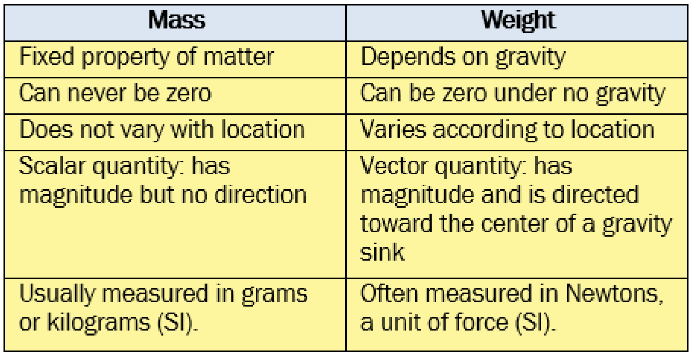
Water potential: Expression describing the energy status of water with reference to pure, free water at zero potential. Water potential can be defined as the potential energy per mole, per unit mass, per unit volume, or per unit weight. A gradient of water potential is the driving force for the displacement of liquid water in a system. Water potential is symbolized by the Greek letter psi, Ψ. Subscripts are sometimes added to define components of water potential: Ψ_m stands for matric potential, Ψg, gravitational potential, etc.

Weight: Force applied to a body in a gravitational field. Weight is a body's mass multiplied by the acceleration of gravity:

$$W = m \times g$$

where weight is denoted by W.

In Earth's gravitational field a body that is not restrained will accelerate toward the center. The restraining force is equal to or represents the weight of the body. For example, when a body is placed on a scale, the spring mechanism acts as the restraining force. The weight of a body will vary at different places on Earth's surface due of differences in gravitational acceleration. On the other hand, the mass of a body is fixed and remains constant anywhere it is measured. The following table compares the attributes of weight and mass.



Mass	Weight
Fixed property of matter	Depends on gravity
Can never be zero	Can be zero under no gravity
Does not vary with location	Varies according to location
Scalar quantity: has magnitude but no direction	Vector quantity: has magnitude and is directed toward the center of a gravity sink
Usually measured in grams or kilograms (SI).	Often measured in Newtons, a unit of force (SI).

Work: Defined as the action of a force through a distance, without regard to time. The notion of *displacement* of a body through a distance is central to the definition of work. Work is computed as the product of force x distance, and is measured in units of foot-pounds (ft-lb, English) and Newton meter (N•m, metric).

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