
# Technical Note 7. Ag Water Literacy I.

## 7.0 Preamble

Water, written as the chemical formula $H_2O$, is required by all living organisms. Life processes such as cell division, growth, reproduction, and metabolism take place in water. Water is supplied to plants through the young root hairs as they grow into the pore space between soil particles. Water lubricates the pore linings, allowing roots to penetrate easily. Water also gives mobility to soil microbes and dissolved plant nutrients. Without a constant supply of water during its life, no plant could reach maturity. This is true for the desert-dwelling cactus as for the plants we grow for food, fiber, energy, and shelter. While plants are actively growing, even a single day without water can result in substantial losses and even death.

About 71% of Earth's surface is covered in liquid water. In considering solid, liquid, and gaseous forms, $H_2O$ ranks as the most ubiquitous molecule in nature. Each year, about 111,000 $km^3$ of water precipitates on the land surface. On average, 70% of this water returns to the atmosphere as water vapor through ***evapotranspiration*** (Ajami 2020). The soil serves as a reservoir for water absorbed from rainfall or irrigation, which plants can use between additions. Water in the soil is, however, different from that of rainwater, or water from a spigot, for two reasons:

- The attraction between water molecules and soil particles modifies the liquid properties of soil water.
- The water in soil is never pure, but contains a wide variety of dissolved substances, including 14 of the 17 known plant-essential nutrients.

Despite the soil's very high capacity to absorb water, water supply remains the primary limiting factor in terrestrial agroecosystems.

## 7.1 Global Distribution of Water

Table 7.1 breaks down the global distribution of water by reservoir. Note that the amount of water held in the soil is a minute fraction of the total water. On the other hand, groundwater is the third-largest reservoir but comprises only 1.7% of total water.

The oceans are, by far, the largest reservoirs of water. However, we can't drink salt-laden ocean water or use it for watering plants. Only 2.5% of the total water supply is fresh enough for human or plant consumption, and about two-thirds of this is frozen.

Water is a highly mobile substance, constantly circulating in and out of global reservoirs. The reservoirs in Table 7.1 may gain or lose water, but the total supply remains constant. This contrasts with the supply of water in the reservoirs, which may store water for long, short, or intermittent periods. For example, some water that infiltrates the soil via rainfall or irrigation may be absorbed by plants. This water is returned to the atmosphere through ***transpiration***, so the soil and biological reservoirs are in constant flux. However, the water in glacial ice changes little, so the supply is relatively constant.

The movement of water from one place to another in Earth's biosphere is called the *hydrologic or water cycle* (Figure 7.1.1). At any given time, only about 0.005% of Earth's water supply is moving through the cycle, but it is still a large amount of water. The hydrologic cycle is a continuous, open-ended process driven by solar radiation and the ***evaporation*** of water.

**Table 7.1** Distribution of Water on Earth

| Reservoir | Water Volume (1,000 $km^3$) | Percent of Freshwater | Percent of Total Water |
|---|---|---|---|
| **Salt Water** | | | |
| Oceans | 1,338,000 | ---- | 96.54 |
| Groundwater-saline | 12,870 | ---- | 0.93 |
| Lakes-saline | 85.4 | ---- | 0.006 |
| **Fresh Water** | | | |
| Frozen[a] | 24,064 | 68.7 | 1.74 |
| Groundwater-fresh | 10,530 | 30.06 | 0.76 |
| Permafrost | 300 | 0.86 | 0.022 |
| Lakes-fresh | 91 | 0.26 | 0.007 |
| Soil | 16.5 | 0.05 | 0.001 |
| Atmosphere | 12.9 | 0.04 | 0.001 |
| Wetlands | 11.47 | 0.03 | 0.001 |
| Rivers | 2.12 | 0.006 | 0.0002 |
| Biological | 1.12 | 0.003 | 0.0001 |
| Total Water | 1,386,000[b] | | 100‡ |
| Total Freshwater | 35,029 | 100‡ | |

*Source: adapted from Shiklomanov 1993*
[a] Glaciers, permanent snow cover
[b] rounded to the nearest million $km^3$
‡ may not sum to 100% due to rounding

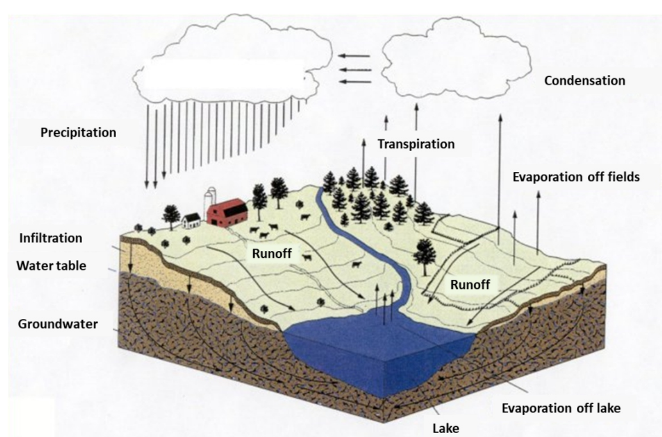



**Figure 7.1.1** The hydrologic or water cycle. *Source: USGS*

## 7.2 Water as a Substance

Water is a peculiar substance with no natural substitutes or replacements. It is the product of two light hydrogen atoms and a 16-fold heavier oxygen atom joined together by strong chemical bonds called ***covalent*** bonds. The average mass of water is 18.02 atomic mass units (amu) or 18.02 grams per ***mole***. There are several ways to visualize a water molecule. But for our purposes, a simple cartoon will suffice:

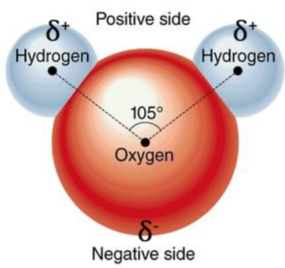



**Figure 7.2.1** A water molecule, chemical formula: $H_2O$. Note that the size of the atoms represent relative differences in charge density, not atomic radii which are actually quite similar for hydrogen and oxygen atoms based on their positions in the periodic table.

There are several things to note in Figure 7.2.1. First, water is a bent molecule, i.e., its molecular geometry resembles that of a boomerang or the letter 'v'. This arises from the interaction of two atomic properties: (1) the relative differences in charge density on the oxygen atom nucleus which has eight positively charged protons (8+) and an equal number of closely held electrons, compared to hydrogen which has only one (1+); and (2) the presence of two, mutually repellent, lone pairs of electrons above and below the plane of hydrogen atoms, which are better visualized by this three dimensional stick and balloon figure:

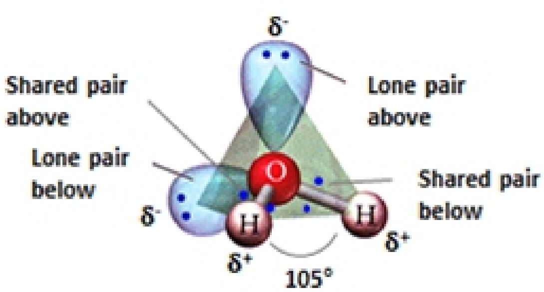
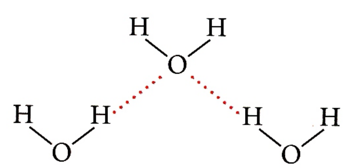


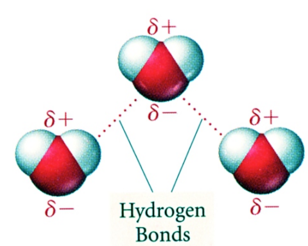

**Figure 7.2.2** Three-dimensional representation of a water molecule. The two lone, mutually repellent, pairs of electrons spread out around the central oxygen nucleus while the shared electron pairs only partially cancel out the positive charge on the hydrogen atoms. This electric charge structure approximates a four-cornered tetrahedron with the oxygen atom near the center and two positively charged hydrogens on two corners. The lone pairs occupy the remaining two corners. *Image source: modified from Tro 2011.*

This creates a tetrahedral electron 'cloud' geometry, in which the relative forces exerted by the two lone electron pairs around the oxygen nucleus cause the bond angle between the oxygen atom and the two hydrogens to shrink to 105°, effectively bending the water molecule, as shown in Figure 7.2.1[1]. The lone pairs of electrons do not participate in bond formation; as the name implies, they simply exist. The other two pairs of electrons participate in bond formation with the two hydrogen atoms, represented by the line segments connecting oxygen and hydrogen in Figure 7.2.1, and by the sticks in Figure 7.2.2. Despite the partial electron-cloud geometry, the water molecule is overall electrically neutral.

The greater number of closely held electrons in the oxygen atom makes oxygen more electronegative, i.e., it attracts electrons more strongly than hydrogen. As a result, there is a net transfer of charge from the hydrogen atoms to the oxygen atom, leading to an unbalanced distribution of charge within the water molecule. Due to these unbalanced charges and the bent structure of water, the positive and negative charge centers do not cancel each other out. In liquid water, this produces a net ***dipole moment*** and a net force. These partial charges, symbolized by the small delta plus δ+ or delta minus δ- in Figures 7.2.1 and 7.2.2, explain the apparent ***polar*** nature of the water molecule.

In a water molecule, the separation of charge is located within the H-O bonds. Such bonds, called ***polar covalent*** bonds, allow the molecule to interact with the dipoles in other molecules, creating a ***dipole-dipole moment***. The opposite charges on hydrogen and oxygen atoms also allow water molecules to attract neighboring water molecules via ***hydrogen bonding***[2]. The electrostatic force of attraction in hydrogen bonding, though relatively weak compared with covalent bonding, is strongest when the O-H bond from one molecule points in the direction of a nearby oxygen atom such that the three O-H-O atoms fall within a straight line:




[1] More precisely the bond angle given is 104.5°, considered the most thermodynamically stable. The bend and stretch (length) of water molecules may exhibit values away from this depending on energy state. Bond angles other than 104.5° are considered "mean" or 'approximate" values for a given energy state.

[2] Another force of attraction between molecules, called London dispersion forces, depends on the probability distribution of electrons within their orbitals at a given moment. These are very weak forces relative to hydrogen bonding and are not considered here.

One water molecule can participate in four hydrogen bonds with other water molecules. This attraction between adjacent water molecules, combined with the high density of molecules due to their small size, produces strong cohesion between molecules that is responsible for water's liquid nature at standard pressure (1 atm) and ambient temperatures 0° to 100° C.

The combined effects of cohesive hydrogen bonding and polarity impart special properties to water, for example:

- **Capillarity**, from the combined effects of adhesive and internal cohesive forces, the last contributing to the "surface tension" of water molecules. Capillarity explains the behavior of water retention in soil, and in the conducting (xylem) tissue in plants. Actively growing land plants maintain a continuous flow of water between the soil and roots through their conductive tissue to the sites of evaporation in the leaves (stomata).

- **Incompressibility**, from the high density (1 g/cm$^3$ at 4° C) packing of molecules and strong intermolecular bonding (Figure 7.2.3). This means that water uptake by plants can generate cell expansion, and that intracellular hydrostatic pressure can help to support the plant. It also explains the phenomenon of soil consolidation whereby water is squeezed out of the soil mineral fabric in response to external loading (gravitational, foot or machinery traffic).

- **Universal solvent**, from its polarity and high relative **dielectric permittivity** (78.3 at 25°C), the latter governed by the tendency of water molecules to polarize, or orient atomic charge within an electromagnetic field (Figure 7.2.3). Polar and ionic substances, including acids, alcohols, and mineral salts, dissolve readily in water. This is crucial for life on Earth because many biologically important molecules are electrostatically charged and dissolve in water, including the mineral salts needed for plant growth and the organic products of photosynthesis, which are transported throughout the plant as water-soluble substances. Modern water-based dielectric sensors ranging from stationary probes to airborne microwave radiometers quantify changes in water's relative dielectric permittivity to accurately measure environmental conditions.

- High **specific heat capacity** (4.18 J/g @ 25°C) and **heat of vaporization** (~22.6 kJ/kg or 40.7 kJ/mol @ 100° C, normal boiling point). These properties result from hydrogen bonding between neighboring water molecules, with far-reaching effects: moderating temperature shifts near large bodies of water, and within the soil; keeping water in a liquid state over a wider temperature range than most common substances; providing an effective mechanism for thermoregulation in plants via transpiration, and in animals via perspiration.

- **Insulator**, due to minimal charge carriers in a pure state.[3]

[3] This applies to theoretical idealized pure water only, not the stuff from your faucet. Ordinary "natural" water contains dissolved ions and will conduct electrical current.

- **Transparency** to visible light (~390-780 nm wavelength) and **opacity** (i.e., absorbing) to ultraviolet (<200 nm), near- to -mid infrared (~1 μm – 10 um) and far-infrared (~10 μm – 1 mm) and microwave (~1 mm – 15 cm) radiation (Figure 7.2.4). Water's transparency and opacity are exploited in microwave ovens, heat exchangers, and remote sensing applications. It also permits photosynthesis and oxygen generation by plants in aquatic environments.

- Water's high **heat of fusion** (6.02 kJ/mol @ 0° C, the melting point) is exploited for frost protection via overhead sprinkler irrigation, particularly fruit crops. This works for two reasons: (1) when water changes from liquid to solid ice, heat of fusion is released to the air it comes into contact with at a rate of 335.2 J/g of water; and (2) heat of fusion can maintain temperature at or very close to 0° C, i.e. provide an insulating effect, if an adequate amount of water is applied and sprinkler irrigation is not terminated early.

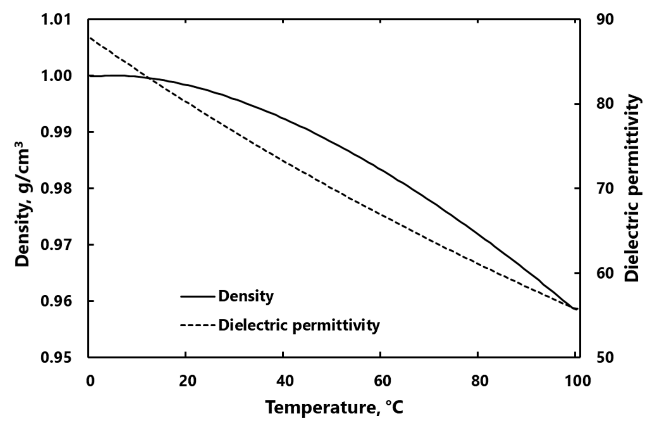



**Figure 7.2.3** Density and dielectric permittivity of water as a function of temperature. The density of pure water reaches a maximum at 4°C, decreasing on either side of this point. This anomalous behavior has far-reaching implications for the state of Earth's biosphere and its living organisms. In contrast, the dielectric permittivity decreases with increasing temperature between 0° and 100°C.

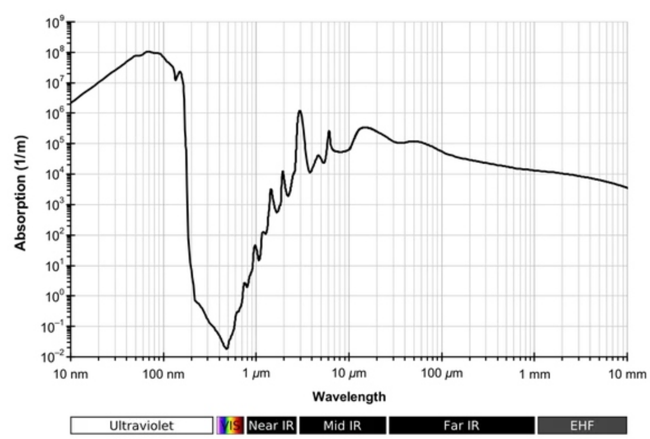



**Figure 7.2.4** Absorption spectrum of water. This panel shows the absorption coefficient α (y-axis) as a function of wavelength (x-axis), in units of inverse meters (1/m). The x-axis is trimmed at 10 mm in the microwave region, but absorption extends further out to ~15 cm. *Image source: Wikipedia*

## 7.3 The Soil-Water-Food Nexus

The availability of ground and surface water primarily determines patterns of human settlement. The so-called 'hydraulic' civilizations of ancient Mesopotamia: Akkad, Babylonia, and Sumer, and Nilotic Egypt, all have in common that they were located in or between river valleys in proximity to surface water for irrigation. Water-conveyance techniques such as the *saqiyah*, Archimedes' screw, and *shadoof* were developed to lift water into irrigation canals and basins (Figure 7.3.1). In Egypt, farmers relied on the annual flooding of the Nile River to replenish fertility and flush excess salts from the root zone. Similar works appeared in China and India. In North America, the famous Hohokam irrigation canal system near Phoenix, Arizona sustained agriculture for several hundred years. While the ancients lacked scientific knowledge of soil, water exchange, and removal mechanisms, their civilizations flourished because people learned from the clear signs of plant stress when water supplies were deficient. They recharged the soil reservoir through irrigation.

Nothing has changed. Irrigation engineers still pay careful attention to design parameters, including the soil and groundwater. Farmers must manage irrigation systems to achieve efficient production and prevent the undesirable buildup of ***soluble salts*** in the crop root zone. Computer programs are written to optimize water-use efficiency. Today, irrigation accounts for about 70% of global groundwater diversions annually, and for more than 90% of total consumptive water use, including surface water (FAO 2011; Siebert et al. 2010). Just under 20% of the world's cultivated land area is irrigated (FAO 2011) yet 40% of the world's food supply comes from irrigated agriculture (IMechE 2013). It's fair to say that the capture, storage, and mobilization of water for agriculture have been, and will continue to be, a key factor in satisfying the ever-growing human demand for food, fiber, energy, and shelter.

Soil is the main reservoir supplying water directly to food crops. Understanding the behavior of water in the soil is, therefore, vital to characterizing crop response to water deficit or saturation. Typical responses of crop plants to soil water include germination, plant stand, tillering, leaf area, flowering and pollination, ripening, nutrient uptake, harvest index, dry matter, and seed yield and quality. But how do we describe and quantify the processes driving water movement through the soil, uptake by plants, and transpiration from plant canopies?

To address these questions, we must understand the fundamental forces that impart motion to a material body, such as water. This leads inexorably to the laws of ***thermodynamics,*** which, in classical physics, are the central dogma describing the phenomenology of change in any system. While a whole discourse on thermodynamics is beyond the scope of this Technical Note, intrepid dirt hogs can get the gist of water exchange in the agricultural field environment by considering a simple case scenario, such as described below.

In the field of ***water balance***, water flow is partitioned into components described quantitatively in terms of mass. Similarly, the ***energy balance*** accounts for the exchanges driving the transfer of mass, in this case, water at 18.02 g/mol, through the system. The status of water in the system

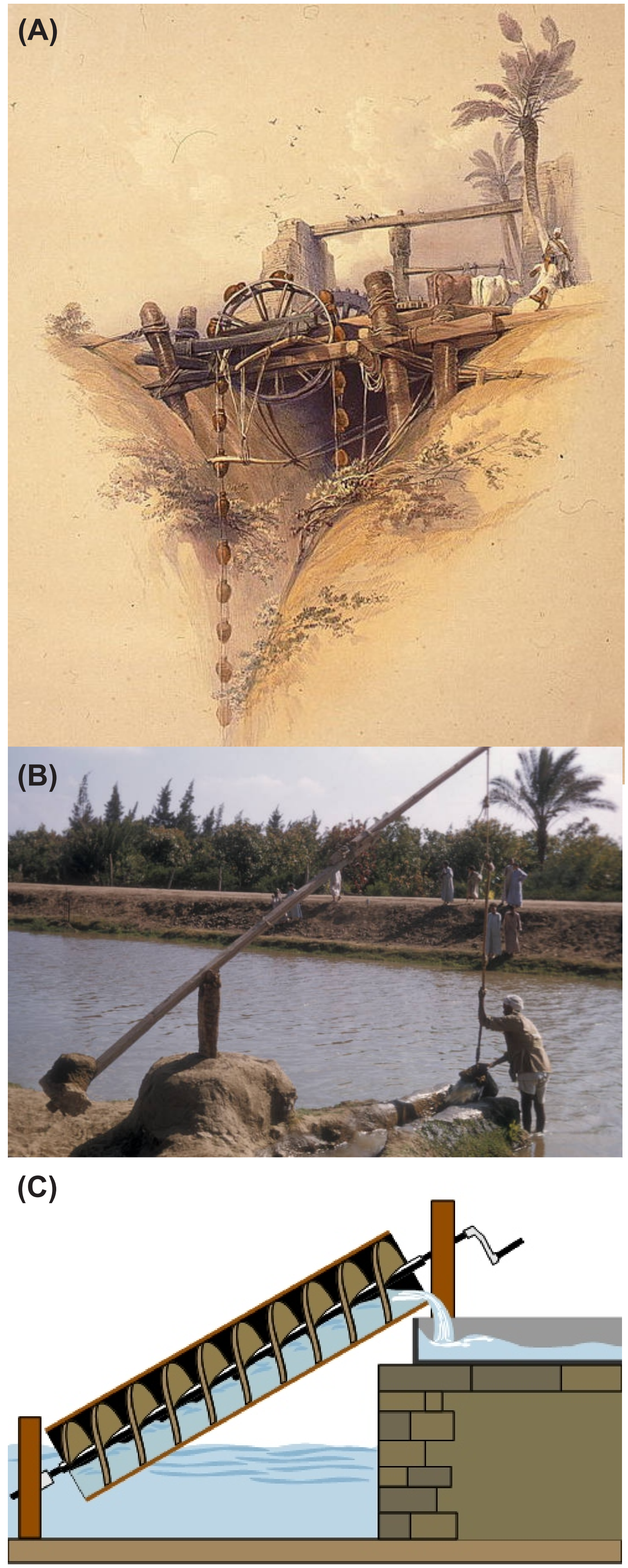



**Figure 7.3.1** Water conveyance techniques pioneered by the "hydraulic" civilization include (**A**) the saqiyah or Persian water wheel; (**B**) the Egyptian shadoof, still utilized in many parts of the world; and (**C**) Archimedes' water screw, attributed to the Greek mathematician and inventor Archimedes but known long before his time. *Image source (**B**) University of Wisconsin.*

at a given time, whether accumulating or depleting, is governed by the universal *conservation of mass and energy* embodied by the ***first law of thermodynamics***. Collectively, the components of this system are known as the soil-plant-atmosphere continuum, or SPAC (Phillip, 1966).

Unlike the hydrologic cycle, the SPAC is a near- and sub-surface phenomenon where "continuum" describes an interconnected, physically integrated and dynamic system where the exchange of water occurs in response to differences in ***potential energy*** (Figure 7.3.2). That is to say, water always moves from a region of higher total potential energy to a region of lower potential energy, i.e., "down the potential energy gradient" in accordance with the ***second law of thermodynamics***. The movement is either by ***mass flow*** or ***diffusion***.

Using the analogy of an electrical circuit, water moving down a potential ***gradient*** flows in the direction determined by the *difference* in total ***water potential*** between two points in the system. The water may be in liquid or vapor form. In general, water moves from the soil to the plant to the atmosphere in a continuous stream because that is the direction of the water potential gradient, i.e., high to low. Different components of water potential are essential at different points in the SPAC. We'll delve more deeply into water potential in Technical Note Part II. But for now, let it be said that ***potential*** is the difference in free energy between a substance and its reference state that causes motion, just like the flow of electrons in a circuit (current).

The nature and number of resistances determine the velocity of water in the SPAC. If the potential difference between two points in the SPAC is zero, no exchange of water is possible according to the law of conservation of energy. This is akin to saying no current (movement of electrons) can flow between two equipotential points in an electrical circuit. Furthermore, the conservation of mass states that the sum of water entering the SPAC must equal the sum removed, since no water can be created or decomposed in the system. In a soil body of finite volume, this means that water content cannot increase without external addition, nor diminish unless removed to the atmosphere or percolated to the groundwater table (Hillel, 1998). In short, any attempt to quantify and control the availability of soil water in the SPAC must reckon with the laws of conservation of mass and energy and the laws of entropy characterizing the processes of energy exchange (the first and second laws of thermodynamics). To illustrate, let's follow a stream of water as it circulates through the SPAC as shown in Figure 7.3.2.

Say that we apply an arbitrary quantity of water to an agricultural field through an irrigation sprinkler. Water exits the sprinkler nozzle under pressure and descends to the ground surface under gravity's pull. Water droplets enter the soil due to permeability, the property that allows liquids or gases to pass through a material. The movement of water into the soil body is called ***infiltration***. If there is no resistance to water entry at the surface, i.e., permeability is high, all the water will infiltrate. If the permeability is low, only a fraction infiltrates, and the rest accumulates on the surface, where it may eventually be discharged as runoff or relocated in the field as ***run-on***. If the pore spaces in the soil root zone are small enough, they may exhibit ***capillarity***, a fluid-retention process arising from the interaction of water

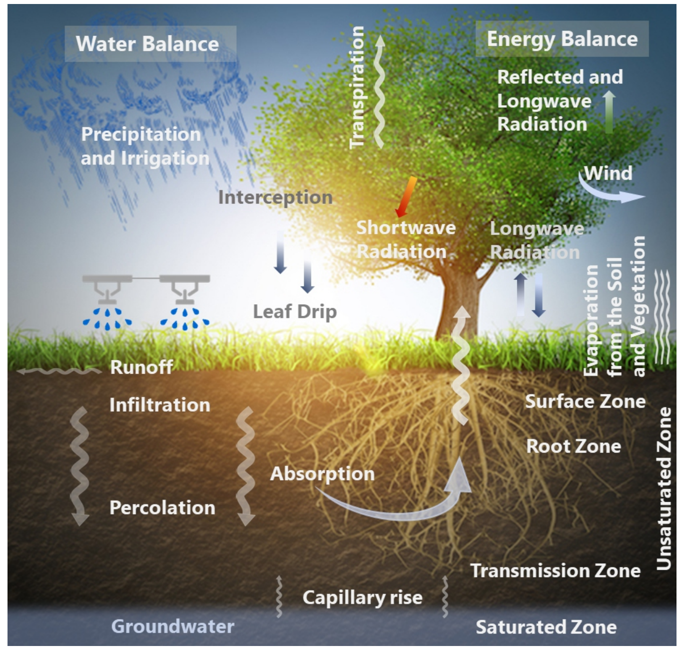



**Figure 7.3.2** Conceptual diagram of the soil-plant-atmosphere continuum (SPAC). The SPAC represents a physically and dynamically integrated near– and sub-surface system. Differences in potential energy govern the possible flow of water in the SPAC, whereas the nature and number of resistances govern the velocity of flow. The agricultural field water balance accounts for all water added to, subtracted from, and accumulated within the surface and root zones of the SPAC.

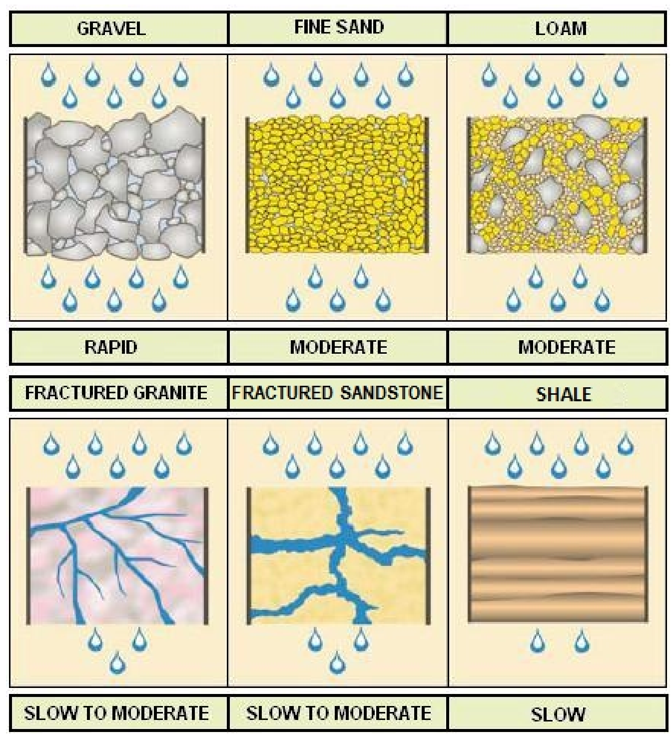



**Figure 7.3.3** Permeability of different soil and rock materials. *Source: modified from Ontario Ministry of Agriculture, Food, and Rural Affairs.*

with mineral surfaces. In time, pores may become saturated to the point where they cannot accept any more water. At that point, runoff begins. The runoff rate may range from 0% to 50% of the water applied. Runoff is counted as a loss to the system because it flows downhill to ditches, streams, and rivers.

The property of permeability arises from *porosity*, which is the existence of air voids, or pore space, in a substance. Soil is composed of a mixture of mineral solids and pore spaces in different proportions. In contrast, the permeability of the soil's parent material, rock, depends on the rock type and the amount of weathering (Figure 7.3.3). Granite, a very dense *igneous* rock, is essentially impervious to water. In a granite stratum, groundwater seeps mainly through fractures in the rock. Sandstone is a *sedimentary* rock composed of irregularly shaped sand particles and is semi-permeable to water. Shale, composed of highly compressed plate-like clay particles, is only very slowly permeable.

Once water has entered the soil, 10% to 30% may percolate deep into the profile, where it eventually adds to or recharges the *groundwater* reservoir. Another 30% to 65% will remain in the soil's ***unsaturated zone***. The boundary between the soil's unsaturated and ***saturated zone*** is the ***water table***. Water held in the unsaturated zone above the water table is commonly referred to as 'soil moisture', whereas water in the saturated zone below the water table is called ***groundwater***. Groundwater may be diffused within the soil mineral fabric or occupy fractures in the rock strata.

Groundwater in the saturated zone that can store, transmit, and yield a useful quantity of water is called an ***aquifer***. About one-third of Earth's freshwater is stored in aquifers and is commonly extracted by means of a well. If the water table is shallow, water may seep to the surface as springs. Where there is no outlet for groundwater seepage, swamps and bogs form; otherwise, the seepage flows into streams, which feed into larger surface water bodies such as rivers, ponds, and lakes. The speed of soil and groundwater movement is very slow —measured in a few meters or less per year —compared to that of unconfined surface water. This is due to the retarding forces of ***adhesion*** and ***surface tension*** inherent to capillarity. Capillarity is a significant phenomenon in nature that we cover in detail in Part II of this Technical Note. Suffice to say, capillarity is responsible for accumulating water in the ***rhizosphere*** (surface-active area around the root) long enough for plants to absorb it.

Some water in the saturated zone may migrate upward into the unsaturated ***transmission zone*** via capillary rise. The height of capillary rise depends on the distribution of pore sizes in the soil, but, in general, water accumulated via capillary rise accounts for less than 10% of the system.

As mentioned previously, capillary forces hold water in the rhizosphere, where it is accessible to plants. The fraction of plant-available water depends on soil mineral composition but is generally 30% to 70% of the rhizosphere's total water content, of which about 50% can be depleted under managed irrigation. Also, liquid water in the surface zone in Figure 7.3.2 may evaporate into the atmosphere, removing 15% to 40% of the system, depending on factors such as plant cover, solar radiation, temperature, atmospheric vapor pressure deficit, wind speed, and thermal conductance. Finally, 15% to 30% of the water is lost through transpiration, a process by which water is transferred from the plant to the atmosphere as vapor. Ultimately, less than 1% of the water absorbed by plants takes part in metabolism, i.e. carbohydrate synthesis, respiration, and regulatory processes (Gutschick 1997). The rest contributes to internal hydrostatic pressure, maintaining the shape and solidity of various plant organs while permitting cell enlargement despite external pressure. Water loss via transpiration is thus considered a reasonably accurate measure of the amount of water the plant removes from the soil.

In summary, the SPAC is an interconnected network of water exchange pathways. That said, in agronomy, we are mainly interested in managing the water balance in the agricultural field environment to offset losses from transpiration and evaporation, collectively known as evapotranspiration ($ET$). There are various methods of quantifying $ET$; one of the most widely used is described by Allen et al. (1998) in the classical paper FAO 56. Water accumulation or depletion in the soil root zone can also be quantified by using in-situ sensors, enabling the irrigation manager to monitor changes in water content with high accuracy.

Supplying water to plants is not just about turning on the irrigation. We need to know when it's time to irrigate, for how long, and when to turn it off. Intuitive knowledge of water supply sustained the hydraulic civilizations of 8,000 years ago. But mobilizing that supply is just as urgent today to address the global challenges of sustaining food, energy, and shelter for all humanity while protecting the environment and contending with the inevitable consequences of climate forcing. In Part II of this Technical Note, we'll describe the different measures of soil water content and further explain their practical application to agronomics.

## Core Intelligence

***Adhesion***: Refers to the ability of a substance to stick to an unlike substance. The opposite is *cohesion*, the attraction of like substances. In water molecules, the property of adhesion arises from the *polar* nature of the water molecule, i.e. the tendency for a molecule to have unequal distribution of positive and negative charges within the molecule while remaining neutral overall (see Section 7.2).

***Aquifer***: An underground stratum of water-bearing rock, rock fractures, or unconsolidated material (gravel, sand, soil).

***Capillarity***: Effect wherein a liquid is caused to flow in narrow spaces in the absence of, or in opposition to, external forces like gravity. The effect is observed in the drawing up, or suction, of a liquid into a thin tube, or in porous media such as cellulosic paper, sponges, plaster, etc. Water is propelled by a combination of adhesive forces between liquid water and surrounding surfaces and cohesive forces between water molecules (surface tension) and also known as *capillary action*, *capillary motion*, *capillary effect*, *wicking effect*. In the soil, *capillary water* is water held in capillary pores or “micropores,” corresponding to a tension head >60 cm of water (=0.05 mm equivalent pore diameter).

***Covalent bond***: A Chemical bond that occurs between two or more nonmetal atoms involving the sharing of electron pairs. The result is a molecular compound, denoted $H{:}H$ or $H-H$. The shared electrons interact with the nucleus of both atoms, lowering the potential energy of the molecule. In some nonmetals, the number of shared electron pairs can be double (carbon) or triple (nitrogen) that of an ordinary covalent bond.

***Dipole moment***: A measure of the separation of positive and negative charges within a molecule

***Dipole-dipole moment***: A measure of intermolecular forces exhibited by polar molecules, e.g., water, resulting from an unequal distribution of charge within the molecule. All polar molecules have permanent dipoles that interact with the dipoles of neighboring molecules, i.e., the positive end of one molecule attracts the negative end of another.

***Diffusion***: A Process that causes the spread of a constituent mass within a medium under a gradient of concentration. It originates from the collision of particles that impels them to move in random directions. Diffusion can describe the spread of water, solutes, gases, and heat in a porous medium. Diffusion of water in the soil occurs via near-surface vapor exchange processes (evaporation) or in unsaturated subsurface zones where a thermal (heat) gradient exists.

***Electronegative***: property of an atom expressed by its ability to attract an electron to itself in a chemical bond. An atom in a molecule is said to be more electronegative when it takes a greater share of the electron density from other atoms in the same molecule.

***Energy balance***: The quantitative evaluation of the components of near-surface energy exchange, e.g. absorption, emission, and reflection of visible and short- and long-wave radiation, latent (evaporation to the atmosphere) and sensible heat (air flow) exchanges. In contrast to water balance, energy balance is applied to surface and near-surface (plant canopy) components of the plant-soil-atmosphere continuum (SPAC). Energy balance methods are a scientifically valid approach to estimating evapotranspiration (ET) and, by extension, water flux in the agricultural field environment. Energy balance approaches can also be applied more broadly at the agroecosystem scale as a measure of relative efficiency or net productivity.

***Evaporation***: The transformation of a substance (e.g. water) from liquid form to water vapor form. In the case of solid water (ice), direct evaporation without passing through the liquid phase is known as *sublimation*. Evaporation in the field can occur from the soil surface, free water surfaces (lakes, ponds, rivers), and crop surfaces that have intercepted water from irrigation and/or precipitation. Water evaporated from the plant body is called *transpiration*. In agronomics, evaporation is denoted by the letter E with units of length (millimeters or equivalent).

***Evapotranspiration***: A term joining *evaporation* and *transpiration,* abbreviated ET. The two terms are often combined, particularly when separating E and T in the field, water balance is difficult. Interception of water by plant canopies is usually included in ET even though it is not measured. It should be noted that evapotranspiration refers to all processes of vapor transfer to the atmosphere, i.e., evaporation, regardless of which surface it takes place. In agronomy, ET is measured in units of length (millimeters or equivalent) per unit time (days). Numerous related units describing plant water use and efficiency are derived from it.

***First and second laws of thermodynamics***: The *first law* of thermodynamics states that energy can be converted from one form to another through interactions involving heat, work, or internal energy, but cannot be created or destroyed. Similarly, the conservation of mass states that the mass of a particle or collection of particles never changes over time, no matter how the constituent particles rearrange themselves; in the jargon of chemistry, *the mass of the reactants must equal the mass of the products*. The conservation of energy and mass holds only in closed systems, i.e., systems in which there is no exchange of energy or mass between the inside and the outside.

The *second law* of thermodynamics states that the direction of change in a closed system is always toward a more stable state, or *equilibrium*. Stated another way, systems with high potential energy tend to change in ways that lower their potential energy. The tendency of water to flow from a region of high total potential to a region of low total potential in pursuit of equilibrium follows from the second law.

***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.

***Groundwater***: Water that accumulates beneath the ground surface, usually in permeable strata called *aquifers*. Groundwater can be fresh or saline, or anything in between. Groundwater reserves are generally replenished by rainfall and snowmelt that descend through the soil profile under gravity. Groundwater pooling is caused by the presence of impermeable strata that prevents further descent.

***Hydrogen bonding***: Relatively weak *intermolecular* bonds (on average 2-5% as strong as covalent bonds) that form between hydrogen atoms with a partial positive charge and a more electronegative atom like oxygen. However, the hydrogen bond should not be confused with chemical bonds, e.g., covalent and ionic, which occur between individual atoms *within* a molecule, whereas hydrogen bonds occur *between* molecules.

***Infiltration:*** Describes the entry of water into the soil body at the surface. Soil physical properties, including porosity, aggregate structure, and initial water content, substantially influence infiltration. Infiltration direction is generally vertical, i.e., downward in the soil profile. The forces driving infiltration are gravitational, matric, pressure potential, or a combination of these.

***Mass flow***: Describes the movement of fluids from a region of high total potential energy to a region of low potential energy in accordance with the second law of thermodynamics. Also known as convection flow, mass transfer, or bulk flow. Mass flow accounts for the movement of liquid water and dissolved substances in the soil.

***Mole***: Amount of a substance containing $6.022 \times 10^{23}$ units, or *Avogadro's number*, of that substance:

$$1 \text{ mole} = 6.022 \times 10^{23} \text{ units}$$

The SI unit for mole (abbreviated mol) is defined as:

$$\frac{6.022 \times 10^{23}\, units}{mol}$$

Avogadro's number is a constant, or *proportionality factor*, relating to the *number* of constituent particles of anything (atoms, ions, molecules, sand grains, etc.) in a sample with the amount of substance in that sample. Avogadro's number is derived from the fact that 1 mole of carbon-12 atoms has been experimentally determined to equal exactly 12 grams, which is numerically equivalent to carbon-12's atomic mass in atomic mass units (amu). In turn, this defines the relationship between *mass* and *amount* of a substance, since the masses of all other elements in the periodic table are defined relative to that of carbon-12.

***Permeability:*** In general, the property of a material that allows another substance (gas or liquid) to pass through it. In soil mechanics, permeability is defined as the velocity of water flow per unit hydraulic gradient (difference). Permeability refers to water flowing in any direction and at any point, whereas infiltration describes the downward movement of water into the soil body at the surface. The lower-case letter k commonly symbolizes permeability. Units are distance, or length (millimeters or equivalent) per unit time (minutes, hours, etc.).

***Polar***: State of a molecule exhibiting an unbalanced distribution of electric charge within it.

***Polar covalent***: A covalent bond between two atoms with significantly different electronegativities (cf.), resulting in an unbalanced distribution of electron density.

***Potential:*** The energy stored by a body or substance due to its position, internal stress, electric charge, or other factors relative to a reference state that causes motion or *change over time*. For example, stretching a rubber band is a way of loading it with potential energy. When the rubber band is released, the potential energy is converted to kinetic energy, which can be used to do work. Similarly, electric energy refers to the energy of moving electrons (current), pushed and pulled into motion by the difference in electric charge (voltage) between two points in an electric circuit. Factors contributing to the total potential energy of an object or substance are additive, i.e., the total potential energy is equal to the sum of the potential energies, however defined.

***Potential energy:*** Energy stored in a body or substance that is available to do work.

***Runoff:*** When rainfall intensity exceeds the capability of the soil to infiltrate (infiltration capacity), the fraction of water discharged away in overland flow is called runoff. Runoff from sloping land may flow into nearby ditches, culverts, and waterways, raising water levels. Flooding is a natural consequence of excessive runoff.

***Run-on:*** Describes the relocation of runoff water within a field. Run-on water ponds in local depressions where it eventually infiltrates. This results in a non-uniform distribution of water in the soil profile and may lead to differences in crop rooting, water availability, nutrient uptake, growth, and yield. Fields are typically “crowned” or graded in such a way as to uniformly discharge runoff water to collection ditches.

***Rhizosphere***: Generally referring to the soil and microbial communities found adjacent to or in contact with the roots of living plants. Originally coined in 1904 by the German agronomist and plant physiologist Lorenz Hiltner, the term has been adopted by soil ecologists, who emphasize the holistic view of soil as a living body. In agronomy, the rhizosphere is the zone of active surface and near-surface exchanges between the living plant root and its environment.

***Saturated zone***: That part of an aquifer below the water table, which is in direct contact with the subsoil or rock, and in which usually all pores and fractures are saturated with water. Above the water table is the unsaturated or vadose zone. Water in the saturated zone below the water table is usually above atmospheric pressure. In hydrology, the saturated zone is called the *phreatic* or *groundwater* zone. Its upper limit is generally denoted on maps by an inverted open triangle ▽.

***Soil moisture***: Soil water in the unsaturated zone above the water table is commonly referred to as 'soil moisture'. The words 'moisture' and 'water' are both nouns but have different meanings. Moisture refers to a vapor or condensed liquid that is diffused on or within another substance. Water is a chemical entity, dihydrogen monoxide, or $H_20$ in chemical shorthand. Moisture can refer to any liquid, including solvents, but not necessarily water. The term 'soil water' includes all $H_20$ in the soil without regard to its chemical state (liquid, ice, vapor) or energy status (free, adsorbed, fixed).

***Soluble salts***: Ionic compounds assembled from positively charged *cations* and negatively charged *anions*, that dissociate their constituents during their interaction with a solvent such as water, forming a *solution*. The final concentration of constituents in solution varies with temperature and pressure but should be at least 0.1 moles per liter at standard ambient temperature (25° C) and pressure (1 atmosphere). An example is table salt, sodium chloride, which dissociates into its constituent cation, sodium, and anion, chloride, when dissolved in water. Soluble salt constituents found in the soil are calcium, magnesium, potassium, sodium, chloride, ammonium, nitrate, sulfate, and bicarbonate. High levels of soluble salts often accumulate in the soil when leaching is insufficient. High levels of soluble salts can harm plants; at low levels, they may serve as essential nutrients or do no harm.

***Surface water***: Water that accumulates above the ground surface. This would include freshwater streams, rivers, lakes, wetlands, reservoirs, and creeks, as well as saltwater bodies like the ocean.

***Surface tension:*** A Physical property that exists at the interface of a liquid and a gas, or a liquid and a solid. In water, surface tension arises from an imbalance in the cohesive forces between water molecules in contact with one another and those in contact with the air or a solid. The unbalanced force draws the water molecules together, creating a curved membrane-like interface of greater strength. It is surface tension that supports a steel needle on the surface of a glass of water, even though steel's density is greater than water's (of course, if the needle is pushed, it will sink).

***Thermodynamics***: A Branch of physics that deals with energy and its interconversions in relation to heat, work, temperature, and the physical properties of matter. The behavior of a system can be explained by the four laws of thermodynamics, which describe phenomena such as motion (change in position with respect to time) and prohibit perpetual motion.

***Transmission zone****:* Zone located between the root zone (rhizosphere) and the saturated zone, characterized by relatively uniform water content with depth. The transmission zone extends to the unsaturated or *vadose* zone. Gravitational forces primarily drive water movement in the transmission zone.

***Transpiration***: The process of water movement through a plant and its evaporation from aerial parts, such as leaves, stems, and flowers. Exhalation of water vapor from plants occurs through specialized apertures called *stomata*. Transpiration is driven by the vapor pressure gradient between the normally water-saturated leaves and the comparatively dry atmosphere; the process of transpiration is therefore passive in that no expenditure of energy on the plant's part is involved. Within the leaf, radiant energy from the sun drives the change of water from liquid to vapor phase. In agronomics, transpiration is denoted by the letter $T$ with units of length (millimeters or equivalent). It serves as the basis for numerous derived metrics of plant water-use efficiency.

***Unsaturated zone***: Refers to the portion of the subsurface above the groundwater table. In hydrology, the unsaturated zone includes the capillary fringe, the transmission zone, the rhizosphere (rooting zone), and the surface zone. Soil and rock in the unsaturated zone usually contain air as well as water in their pores. Another term for the unsaturated zone is *vadose zone*. Water pressure in the unsaturated zone is generally less than atmospheric, i.e., under tension. Although the water holding capacity of Earth's unsaturated zone is enormous, water usually does not accumulate there. Thus, it has only a minute fraction of Earth's fresh water. It is, however, the zone mainly responsible for agricultural productivity.

***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 largest subtractions, whereas precipitation and irrigation account for the most significant additions. Crop water used for cellular growth is a minute fraction (< 1%) of transpiration and is often disregarded. Runoff, run-on, capillary rise, and water-table rise are accounted for where they occur. Water balance accounting methods are widely used in research studies and for irrigation scheduling.

***Water table****:* The upper boundary of the groundwater in contact with the unsaturated zone. The water table can be very close to the land surface (within a meter) or very deep (75-100 meters).

## Further Reading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