STEVENS

Soil Geomorphology

A Pedological Guide for Soil Sensor Applications

Application Note 2019

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Horizon	Depth (cm)	% Clay	%Sand	Field Capacity	PWP	Color	Soil Texture
O	2-0					Dark	
A	0-5		22	26%	4%	10YR4.5/2	Silty-Loam
AB	5-8		22	26%	4%	10YR5/3	Silty-Loam
Bw	8-26	10	36	25.2%	8.8%	10YR6/3	Silty-Loam
2Bt1	26-48	13	32	26.7%	9.9%	10YR6/3	Silty-Loam
2Bt2	48-84	17	30	28.9%	12.1%	10-7.5YR 6/4	Silty-Loam
2Bx	84-125	20	30	30%	13.7%	10-7.5YR 6/4	Silty-Loam

Soil survey, silty loam with a fragipan. Soil order: Typic Fragixeralf.

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FORWARD

Soil hydrology is an emerging science with many new applications ranging from water resources, food security, and climate change.

In situ soil moisture data has become key to our understanding of a major component of the hydrological cycle. Soil properties are discussed at length because the soil properties can strongly influence the behavior of water movement and analytical measurements. With the wide variety of applications involving soil moisture sensors, the study of soil geomorphology can provide insight into the interpretation of soil moisture as well as key insight into the vertical and horizontal placement of soil moisture sensors as well as an overall deployment strategy.

SOIL GEOMORPHOLOGY AND PROPERTIES

Soil geomorphology is the science of how soil forms over time. Soil can be defined as the porous media covering Earth's land surface. Soil is complex physically, chemically, hydrologically, and biologically. Soil is composed of mineral components and contains a habitat and ecosystem of micro-organisms that can be both carnivores and herbivores. A spade full of soil contains billions of organisms and thousands of species. Soil represents a significant proportion of the earth's biodiversity. Soil is a living and breathing world that is as biologically diverse as a rain forest.

Knowledge of soil geomorphology and soil properties provides insight into the interpretation of soil moisture data and the vertical or horizontal placement of soil moisture sensors. An understanding of soil properties and formation is very helpful in determining the overall field deployment strategy for meteorological stations making the most out of the available funds and resources.

1.1 / Soil Development

Soil starts off as a rock. Rock falls into three primary groups: igneous rock, which forms from volcanic activity, sedimentary rock, that forms under lakes and oceans, and metamorphic rock which develops with heat and pressure over time. After or during rock formation, the rock may be lifted in elevation by tectonic or other geological processes leading to the formation of hills, mountains and plateaus. As rock ages, it breaks down into smaller components in a process called weathering. The weathering process includes, but is not limited to, wind, rain, temperature changes, erosion and re-deposition, and biological activity. Overtime, the weathering process breaks down and develops the rock parent material leading to the rocks transformation into soil. Many of the chemical properties of soil comes from the rock parent material (Birkeland, 1999). For example, a rock that is high in iron will develop and eventually form iron rich soil. The elemental composition of soil is mostly Si, Al, Fe(III), Fe(II), O, and H.

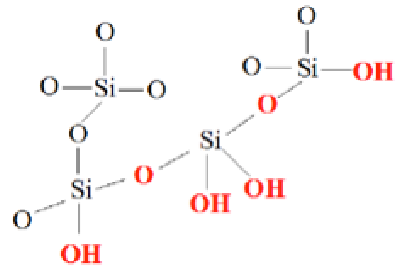

Figure 1 / A typical sand or silt at the elemental and molecular level. "O" is oxygen, "Si" is silicon, "H" is and hydrogen. Soil structure may also include "Al" (Aluminum) and oxidation states of "Fe" (Iron).

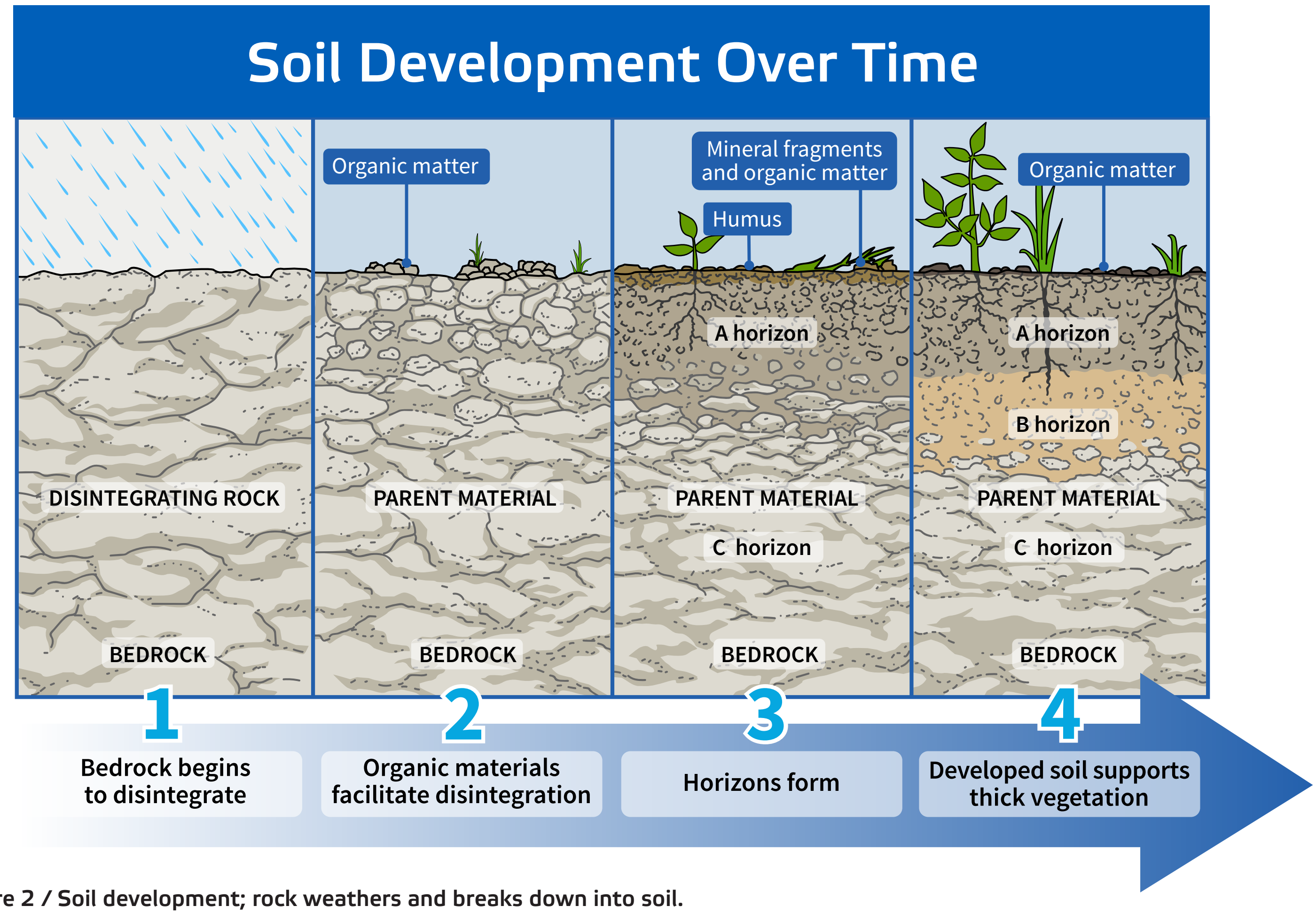

Figure 2 / Soil development; rock weathers and breaks down into soil.

As the rock weathers and breaks down, sand is the first to form. Sand is a miniature rock particle with the same crystallography as the rock parent material. The sand promotes plant growth and biological activity that increases the acidity, which in turn further breaks down the material into arrogate material. As sand ages, the weathering process continues, breaking sand down into smaller particles. The presence of organic solutes from rotting plant material and physical weathering will lead to further transformation of the sand into a silt. Silt is a medium sized soil particle smaller than sand. As the soil becomes more silt rich from the breakdown of the sand, clay films will begin to form. Silt, through chemical and physical weathering, in combination with the dissolved carbonate chemistry in the water, continues to breakdown the material. The formation of clay begins when the molecular structure containing iron, aluminum, and silicon oxidizes and relaxes. Clay particles are fundamentally different at a molecular level than silt. Clay, at the molecular level, exists as a planner framework arrangement of Al, Si, Fe, O and H called a crystal lattice. These clay lattices are typically tetrahedral, and octahedral arrangements of Al, Si, Fe, H and O that pack into a plate or planner configuration (Grim, 1968).

The morphological processes that takes rock to clay films takes anywhere from 10,000 to 100,000 years. The morphological process, climate, biology, and weather are all intertwined. Each influences the development of the other, with water as the driving force for change. This intimate interaction between the soil, water, climate and living organisms is an emerging science called the Critical Zone (Brantley, 2007).

Across these molecular layers of clay particles, a negative charge distribution can occur. At the molecular level, as the silicon and iron relax into a new clay lattice configuration, the silicon and iron are able to hold electrons in a part of the molecule called the d-orbital. This negative charge attracts positively charged cations that can serve as a nutrient for a plant or bacteria. Cations such as potassium, phosphorus, and magnesium will then have a charge/chemical attraction to the clay. The overall strength of the negatively charged character of the soil can be approximated by the CEC (cation exchange capacity expressed in moles per liter). Knowing the CEC of a soil provides insight into how fertile the soil is and generally increases with the clay content. The CEC can be determined by titration or photometry methods (Rowell, 1994).

Clay comes in hundreds of types, each with their own variations to the structure shown in Figure 1.3. The elemental makeup of the rock parent material strongly influences the types of clay that will form in terms of the elemental distribution in the layers and the tetrahedral and octahedral packing. For example, a kaolinite clay with the chemical composition of $Al_2Si_2O_5(OH)_4$ will have one tetrahedral sheet of silica (SiO_4) linked through oxygen atoms to one octahedral sheet of alumina (AlO_6).

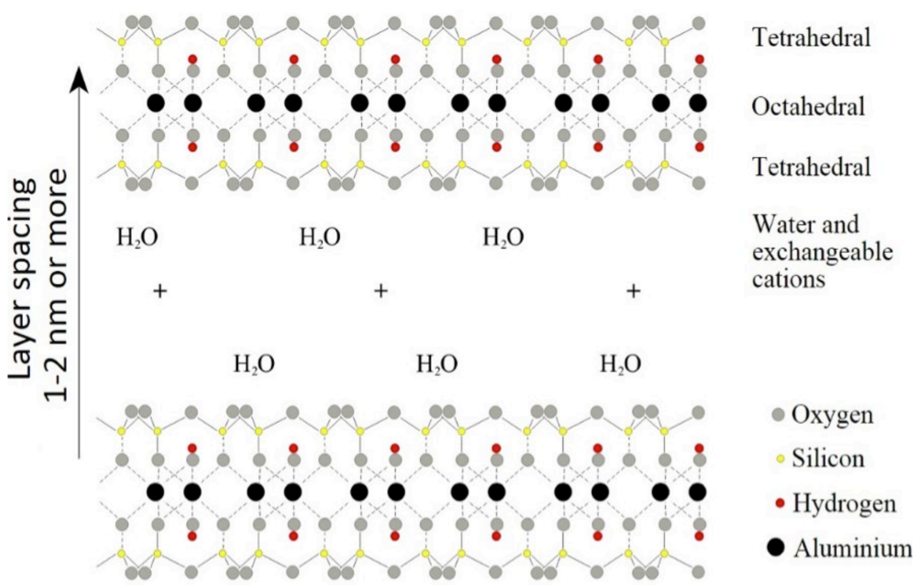

Figure 3 / Molecular structure of a typical Clay.

Kaolinite clays are common in ceramics and will have very different properties than a smectite. A smectite clay is a dioctahedral aluminous species with tetrahedral and octahedral substitutions (McBride, 1994). Smectites can be common in fertile soils that develop under grasslands and can have up to ten times the CEC as a kaolinite.

Table 1 / Particle size distribution of soil based on USDA classification. Note that ASTM and UN FAO classifications may differ slightly.

Mineral Type	Particle size distribution in mm
Gravel	>2
Very course sand	1-2
Coarse sand	0.5-1.0
Medium sand	0.25-0.50
Fine sand	0.10-0.25
Very fine sand	0.05-0.1
Silt	0.002-0.05
Clay	<0.002

1.2 / Soil Texture and Components

Soil is very heterogeneous composition of air, water, inorganic and organic materials. Knowing the soil texture provides insight into the properties of the soil, particularly with the soil's hydrology.

Soils are composed of four main components:

- Mineral particles of different sizes (Sand silts, clays, and pebbles)
- Organic materials from the remains of dead plants and animals
- Water that fills open pore spaces
- Air that fills open pore spaces

If the percentages of sand silt and clay are known, the soil texture triangle can be used to determine the soils' textural class. There are strong correlations between soil textural class and hydrological phenomenon such as infiltration rate, availability of stored water for crops, saturation point, and nutrient holding capacities.

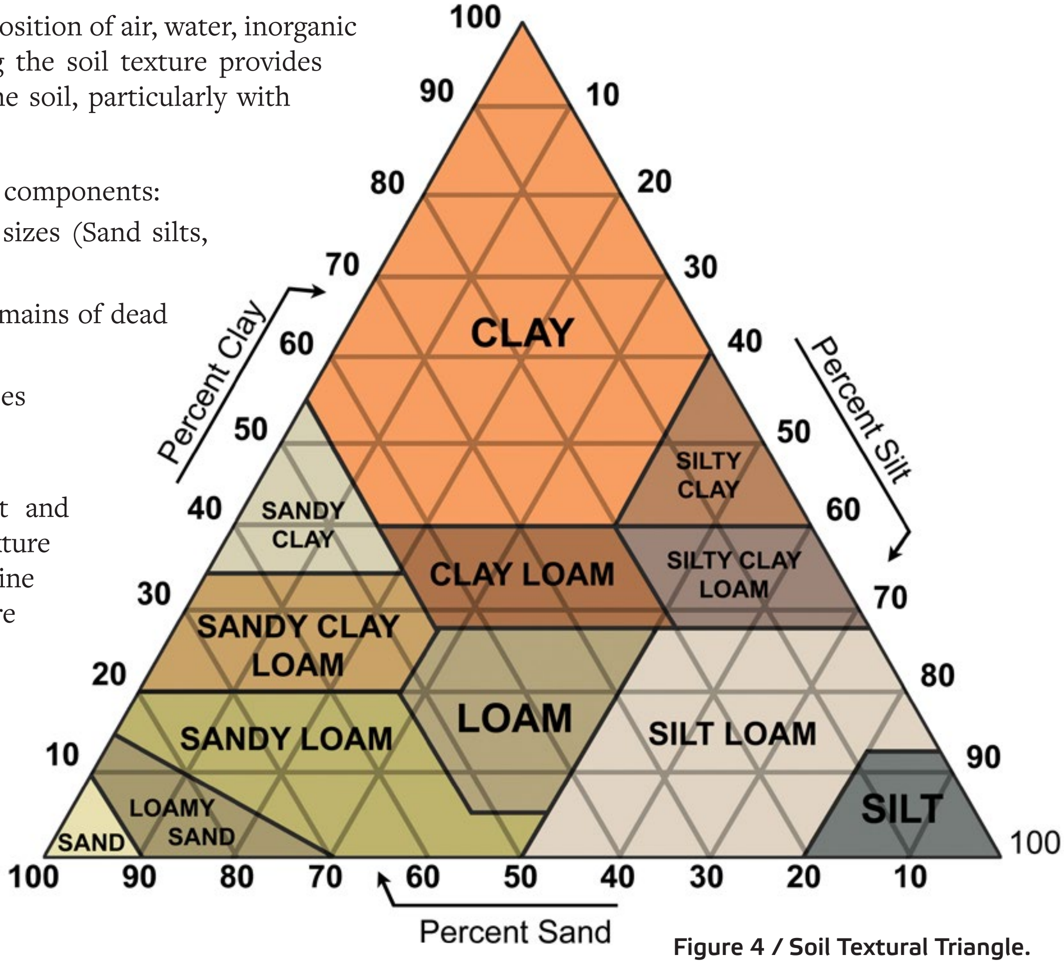

Figure 4 / Soil Textural Triangle.

A typical soil found in forested areas or in irrigated agriculture is on average about 45% mineral, 5% organic matter, and 50% void spaces (or pores) which can be occupied by water and/or air or gas. The percent of soil mineral and organic content can be treated as a short-term constant. The percent of soil water and air/gas content is highly variable whereby a rise in one is simultaneously balanced by a reduction of the other.

Pore space allows for the infiltration and movement of air and water, both of which are critical for life in soil. Compaction, a common phenomenon with soils, reduces this space, preventing air and water from reaching plant roots and soil organisms.

The primary particles of sand, silt, and clay make up the inorganic solid phase of the soil. These particles often aggregate together and other parts of the soil, most importantly organic matter.

In general, the size and spacing of soil particles determine how much water can flow through the soil. The larger the spacing, or pore size, the greater the infiltration rate of free water (water that is not in soil). Thus, sandy soils will have high infiltration rates with free water because pore sizes are large and there are no finer materials to block the pores. The soil texture also influences how much heat and A typical soil found in forested areas or in irrigated agriculture is on average about 45% mineral, 5% organic matter, and 50% void spaces (or pores) which can be occupied by water and/or air or gas. The percent of soil mineral and organic content can be treated as a short-term constant. The percent of soil water and air/gas content is highly variable whereby a rise in one is simultaneously balanced by a reduction of the other.

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Sandy soils drain (free water) under wet conditions better than clay rich soils. The smaller the soil particle size distribution, the slower it will drain. Sometimes silt may have the same particle size distribution as clay, but clay retains water for longer periods of time than silt. This is explained by the shape of the soil particles. Clay particles are planar, whereas silt particles are spherical. The planar plate shaped clay particles trap water, slowing the flow of water.

If the water is not free water, such as water in the pore spaces of soil, the opposite is true. Capillary forces are the primary driver of water once it is in the soil in a process commonly called “wicking”. For example, a wet soil can drain quickly into a clay layer but will not drain into a sand layer due to the stronger capillary forces of the clay. While sand will drain faster on the surface, a sand layer under a silt layer will perch the water and prevent the silt from draining.

An easy way to help determine what type of soil you have is to feel the texture to determine what the primary makeup of the soil is. Grab a baseball size portion of the soil in your hands, wet the soil with water, and work the moist soil with your hands. The stickier it is, the more clay there is. The “soapier” the soil feels, the higher the silt content. Grittiness is indicative of sand. Laboratory tests can be performed to determine the soil’s texture. This is done by a combination of sieving and measuring the changes in specific gravity of the soil water mixture as the silt settles.

In the United States, twelve major soil texture classifications are defined by the USDA. The twelve classifications are sand, loamy sand, sandy loam, loam, silt loam, silt, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, and clay. Soil textures are classified by the fractions of each soil component (sand, silt, clay) present in the soil. Classifications are named for the primary constituent particle size or a combination of the most abundant particles sizes, e.g. “sandy clay” or “silty clay”. A fourth term, loam, is used to describe equal properties of sand, silt, and clay in a soil sample, and lends to the naming of even more classifications, e.g. “clay loam” or “silt loam”.

Texture is important because it influences:

- Water retention
- Flow
- Soil fertility and workability

For example, sand is well aerated but does not hold much water and is low in nutrients. Clay soils generally hold more water and are better at supplying nutrients.

Soil hydrology stands at the forefront of soil health. It is critically important for regulating physical, chemical and biological processes in soils. Soil-water interactions are closely related to and create both positive and negative feedbacks with soil characteristics, landscape features and management practices that are tied to soil health. For example, pore drainage causes a buildup of salinity in the soil which, over time, will stress plant and crops. While too little water will stress a plant, saturated conditions for long lengths of time will also stress plants, making them more susceptible to disease.

Knowing the hydrological behavior of soil is essential for managing and protecting natural and agricultural ecosystems. Soil hydrological behavior determines crop responses to water and nutrients provided by irrigation and fertilization. Soil hydrology also controls deep percolation fluxes of water and nutrients, as well as water and nutrient runoff. It impacts the quality of soil, surface, and groundwater resources.

Water is a critical agent in soil development due to its involvement in the dissolution, precipitation, erosion, transport, and deposition of the materials that soil is composed of. Water is also key to the dissolution, precipitation, and leaching of minerals from the soil profile. Water affects the type of vegetation that grows in a soil, which in turn affects the development of the soil. Soil, water, and living organisms participate in a complex dynamic feedback that shapes the soil properties, ecosystems, climate, and weather.

Soils supply plants with nutrients, most of which are held in place by particles of clay and organic matter. Nutrients may be adsorbed on clay mineral surfaces, bound/absorb within clay minerals, or reside within organic compounds as part of living or dead organic matter. These bound and absorbed nutrients interact with soil water to buffer the soil solution composition (attenuate changes in the soil solution) as soil dampens, dries, as plants take up nutrients, as salts are leached, or as acids or alkalis are added.

Plant nutrient availability is affected by soil pH. Soil pH is a measure of the hydrogen ion activity in the soil solution. Soil pH is a function of many soil forming factors and is generally lower (more acidic) in areas with a lot of weathering and biological activity.

Most plant nutrients, with the exception of nitrogen, originate from the minerals that make up the soil parent material. Some nitrogen originates from rain as dilute nitric acid and ammonia, but most nitrogen is available in soils as a result of nitrogen fixation by bacteria. Nitrogen fixation is the bio-chemical process that takes inert nitrogen (N_2) from the air and converts it to a nutrient form of nitrogen such as ammonia (NH_3).

Soils are one of Earth's essential natural resources, yet they are often taken for granted. Most people do not realize that soils are a living, breathing world supporting nearly all terrestrial life. Soils and the functions they play within an ecosystem vary greatly from one location to another as a result of differences in climate, the animal and plant life living on them, the soil's parent material, the deposition of the soil on the landscape, and the age of the soil.

The use and function of a soil depends on the amount of each component. For example, a good soil for growing agricultural plants has about 45% minerals, 5% organic matter, 25% air, and 25% water. Plants that live in wetlands require more water and less air. Soils used as raw material for bricks need to be completely free of organic matter.

Deploying soil sensors for measuring soil moisture, salinity, temperature level, matric potential, and other characteristics can provide insight to researchers, and irrigators who rely on soil data for their work.

1.3 / Soil Horizons

Each area of soil on a landscape has unique characteristics. A vertical section roughly 1 to 2 meters deep at one location is called a soil profile. The layers of soil in a profile are known as horizons. Soil horizons can be as thin as a few millimeters or thicker than a meter. Individual horizons are identified by the differences between the properties each horizon contains. Some soil horizons are formed as a result of the weathering of minerals and decomposition of organic materials that move down the soil profile over time. This movement, called illuviation, influences the horizon's composition and properties. Other horizons may be formed by the disturbance of the soil profile from erosion, deposition, or biological activity. Soils may also be altered by human activity. For example, builders compact soil, change its composition, move soil from one location to another, or replace horizons in a different order from their original formation.

Soil horizons are distinct layers of soil that form naturally in undisturbed soil over time. The formation of soil horizons is called soil geomorphology or pedology and the types of horizons are indicative of the soil order. Like other natural processes, the age of the horizon increases with depth.

The reason why it's useful to have a soil sensor in each horizon is because different horizons have different hydrological properties. Some horizons will have high hydraulic conductivities and thus have greater and more rapid fluctuations in soil moisture. Some horizons will have greater bulk densities with lower effective porosities and thus have lower saturation values. Some horizons will have clay films that will retain water at longer than other soil horizons.

The horizons with different textural class with have different field capacities and permanent wilting points, two of the most important hydrological parameters for soil. Field capacity is a wet condition in which water is able to drain downward. Permanent wilting point is a drier condition where a plant or bacteria can no longer remove water out of the soil.

Figure 5 / Munsell Color book for identified soil colors and also a good field method for identifying soil horizons. Picture provided by the USDA NRCS.

Figure 6 / Soil horizontal profile of a Argillic Epipedon.

Knowledge of the soil horizons and an accurate soil sensor allows a user to construct a more complete picture of the movement of water in the soil. The horizons that exist near the surface can be 6 to 40 cm in thickness. With increasing depth, the clay content increases, the organic matter decreases and the base saturation increases. Soil horizons can be identified by color, texture, structure, pH, and the visible appearance of clay films.

There are dozens of different kinds of horizons and in general, the older the soil the more horizons that can be identified. In the field while installing soil sensors, a Munsell color book can be used to help identify soil horizons.

Table 2 / Soil Horizons their typical depths and properties.

Soil Horizon	Typical Depth	Features
O	On top of soil, Soil Surface	Composed of mainly Organic material such as dead plants, sticks, leaves and inorganic dust. Also contain live roots.
Oa	On top of soil, Soil Surface	A well decomposed O Horizon with a fiber content less than 17% by volume
A	Under O Horizon and can be 0 to 30 cm in depth	The A horizon is the top soil which is a mixture of highly organic material and inorganic soil.
Ap	Under O Horizon and can be 0 to 30 cm in depth	An A horizon that has been plowed and farmed and has less organic content than an undisturbed A horizon.
B	Under an A Horizon, 5cm to over 100 cm typical. The depth of the B horizons is highly variable and depends on soil and the region. In some areas the B horizon can be many meters in depth.	B Horizons are the subsoil which is characterized by having a minimal amount of organic matter and little evidence of the soil's parent material. It is the developed layers of the soil showing the development of silts and clays.
Bh	Under an A Horizon, 5cm to over 100 cm typical	A Bh horizon is an illuvial horizon that was formed from deposition of silt.
Bk	Under an A Horizon, 5cm to over 100 cm typical	B horizon that is slightly alkaline and has an accumulation of calcium carbonate
Bt	Under an A Horizon, 5cm to over 100 cm typical	A Bt horizon is a well developed B horizon with high concentrations of clay. Older soils (paleosols) many contain many Bt horizons.
Bw	Under an A Horizon, 5cm to over 100 cm typical	A Bw horizon is a younger B horizon and will have a reddish color.
Bx	Under an A Horizon, 5cm to over 100 cm typical	A Bx horizon is a fragipan which a a dense layer of silt that sometime slows water movement and forms from windblown silt called loess.
K	Under an A Horizon, 5cm to over 100 cm typical	Cemented horizon high in Calcium carbonate.
C	Under a B horizon or A horizon or on surface. Variable depths.	Unconsolidated geologic material, sands and gravels. Possibly a parent material.
E	Under an A horizon or within a B Horizon. From 5 to 100 cm in depth typical	Highly oxidized silty sands that are very light in color that form from organic acids from needle leaf trees.

Properties of soil are often discussed in terms of a soil's epipedon. An epipedon is a horizon or a series of related horizons that share properties. A soil's epipedons is a brief characteristic diagnostic description of the soil. With the vast variety of known epipedons, identifying and correlating epipedons to vegetation and other phenomenon is its own sub-discipline of soil science called pedology. We name a few common epipedons here in table 1 .3.

Table 3 / Common Soil Epipedons.

Epipedon	Basic Defining Criteria
Mollic	Highly alkaline with a thick A horizon.
Umbric	Similar to a mollic epipedon but less alkaline.
Histic	Highly organic, poorly drained, anoxic.
Albic	Has B horizon that are lighter in color
Argillic	Well-developed B horizon with moderate to high levels of clay.
Spodic	Soil that contains E horizons above or within a B horizon.
Salic	Saline soil
Cambic	Soil with a Bw horizon and very low in carbonate.
Duripan	Silica Cementation, occurs in arid regions
Fragipan	Dense silt B horizons formed from loesses or other processes
Anthropic	Impacted by humans, agriculture or other activity

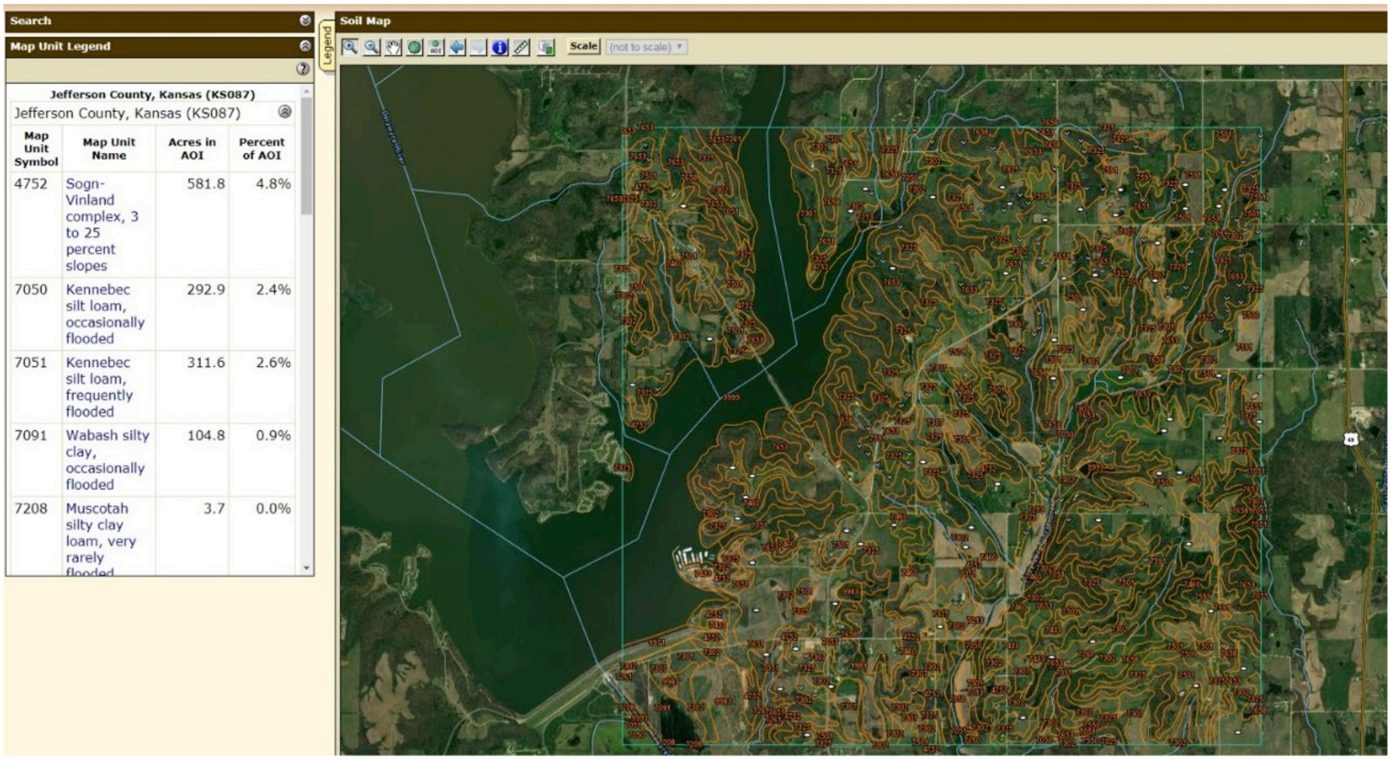


Figure 7 / An example of a soil map. Soil maps and soil analysis data for most places in the United States can be obtained from the US Department of Agriculture NRCS Web soil Survey at https://websoilsurvey.sc.egov.usda.gov Web soil survey smart phone apps are also available.

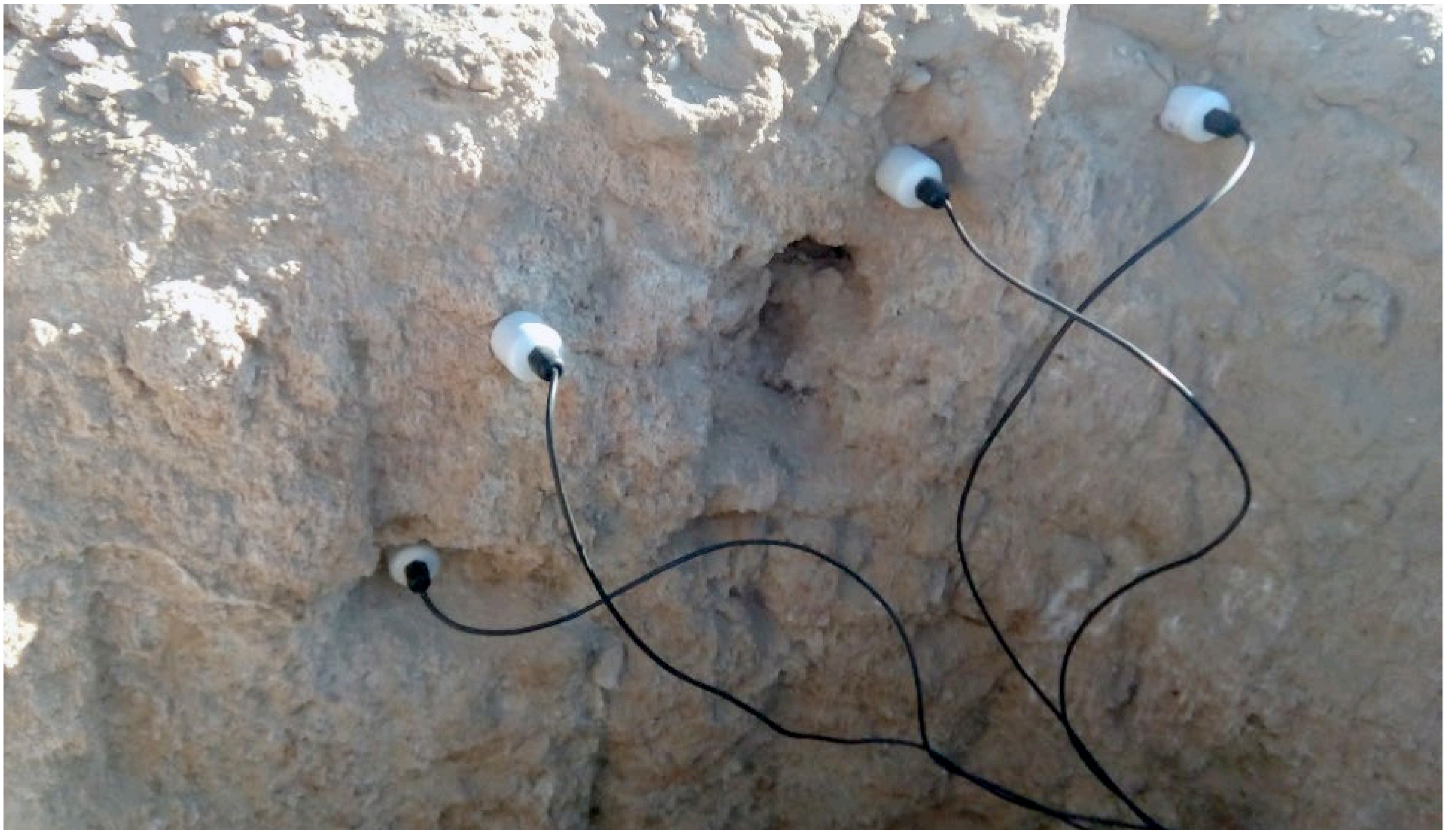


Figure 8 / HydraProbe Soil Sensors installed in duripan epipedon in arid region.

1.4 / Soil Orders and Taxonomy

Soil, just like plants and animals, are broken down by scientists into a hierarchical classification system, which is as follows: orders, suborders, great group, subgroup, family, and series. While there are thousands of types of soil around the world, they can all be classified under 12 major orders (USDA, 2014). A complete guide to the worlds soil types can be found in the latest version of the Keys of Soil Taxonomy, obtained free of charge from the US Department of Agriculture NRCS Soil Survey.

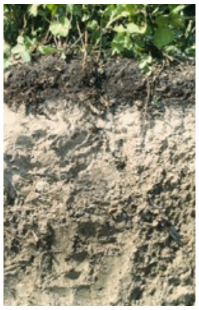
The ocurance and formation of soil orders is based on how the soil changes over centuries, thousands or millions of years.

The different orders arise from many factors including:

- type of rock parent materail the soil formed from
- climate
- type of vegetation present
- floods
- volcanic activity
- availability of water
- and many other factors.

Each soil order is further characterized by suborder, great group, and subgroup.

The 12 Orders of Soil Geomorphology



Alfisols are found in in semiarid to moist areas. They form under forest or mixed vegetative cover and are productive for most crops. Alfisols have argillic horizons,meaning that the B horizons have significantly aged to the point where clay films are developing in layers and around the unit peds of the soil.

Andisols tend to be highly productive soils. They are common in cool areas with moderate to high precipitation, especially those areas associated with volcanic materials. Andisol soils can form from volcanic ash and may contain volcanic glass and amorphous colloidal materials.

Aridisols are soils that are too dry for the growth of mesophytic plants. They often accumulate gypsum, salt, calcium carbonate, and other materials that are easily leached from soil in more humid environments. Aridisols are common in the world's deserts.

Entisols occur in areas of recently deposited parent materials or in areas where erosion or deposition rates are faster than the rate of soil development; such as dunes, steep slopes and flood plains.

Gelisols are soils that have permafrost near the soil surface, have evidence of frost churning or ice segregation. These are common in the higher latitudes or high elevations.

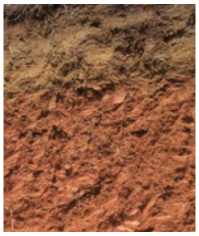
Histosols have a high content of organic matter and no permafrost. Most are saturated year-round, but a few are freely drained. They are commonly called bogs, moors, pears or mucks. Histosol soils may develop anaerobic conditions and are typically very dark in color.

Inceptisols are soils of semiarid to humid environments that generally exhibit only moderate degrees of soil weathering and development. These occur in a wide variety of climates.

Mollisols are soils that have a dark colored surface horizon relatively high in content of organic matter. The soils are base alkalinity rich throughout and therefore are quite fertile. Mollisols develop in arid and semiarid grasslands.

Oxisols are highly weathered soils of tropical and subtropical rain forest regions. They characteristically occur on land surfaces that have been stable for a long time. They have low natural fertility as well as a low capacity to retain additions of lime, fertilizer, clay rich, and are highly oxidized.

Spodosols formed from weathering processes that strip organic matter combined with aluminum oxide from the surface layer and deposit them in the subsoil. These tend to be acidic and infertile. Have a spodic epipedon with an E horizon low clay content and develops under needle leave forests.



Ultisols are soils in humid areas. They are typically acidic soils in which most nutrients are concentrated in the upper few inches. They have a moderately low capacity to retain additions of lime and fertilizer. Ultisol soils are clay rich and have large developed Bt horizons.

Vertisols have a high content of expanding clay minerals. They undergo pronounced changes in volume with changes in moisture. Because they swell when wet, vertisols transmit water very slowly and have undergone little leeching. They tend to be high in natural fertility. Vertisols are shrink/swell clays and, depending on moisture content, can form large cracks during dry periods. They are rich in montmorillonite minerals.

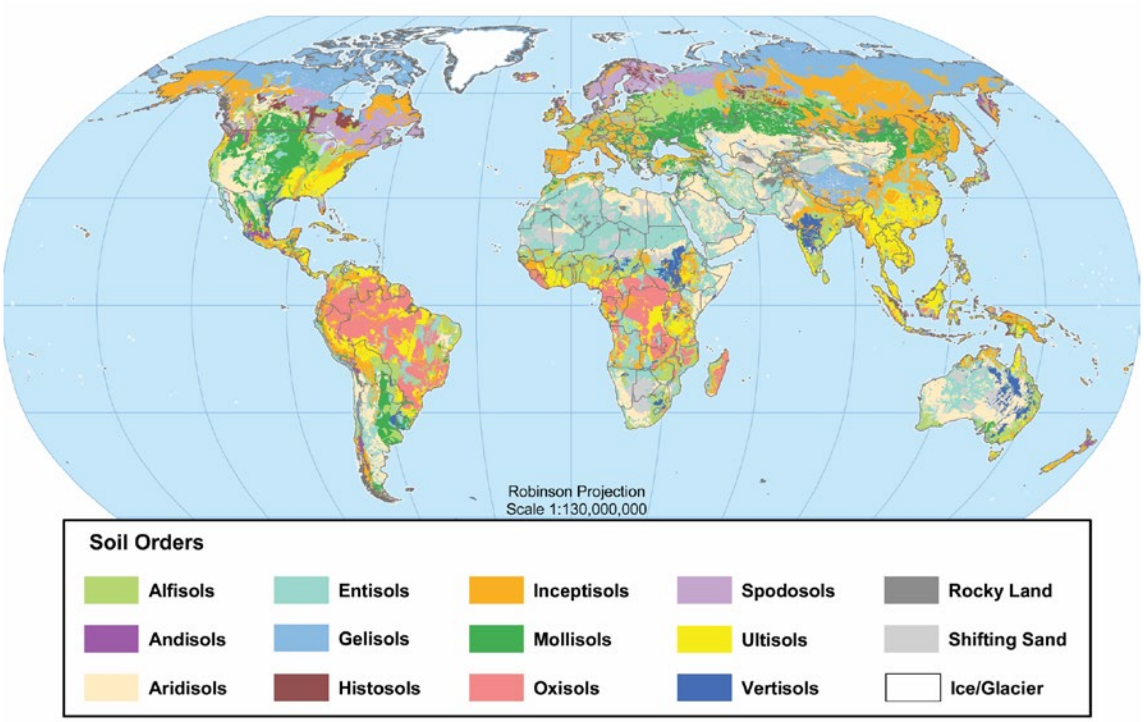


Figure 9 / Global Distribution of Soil Orders. Figure compliments of the US Department of Agriculture NRCS.

Soil Development Chart

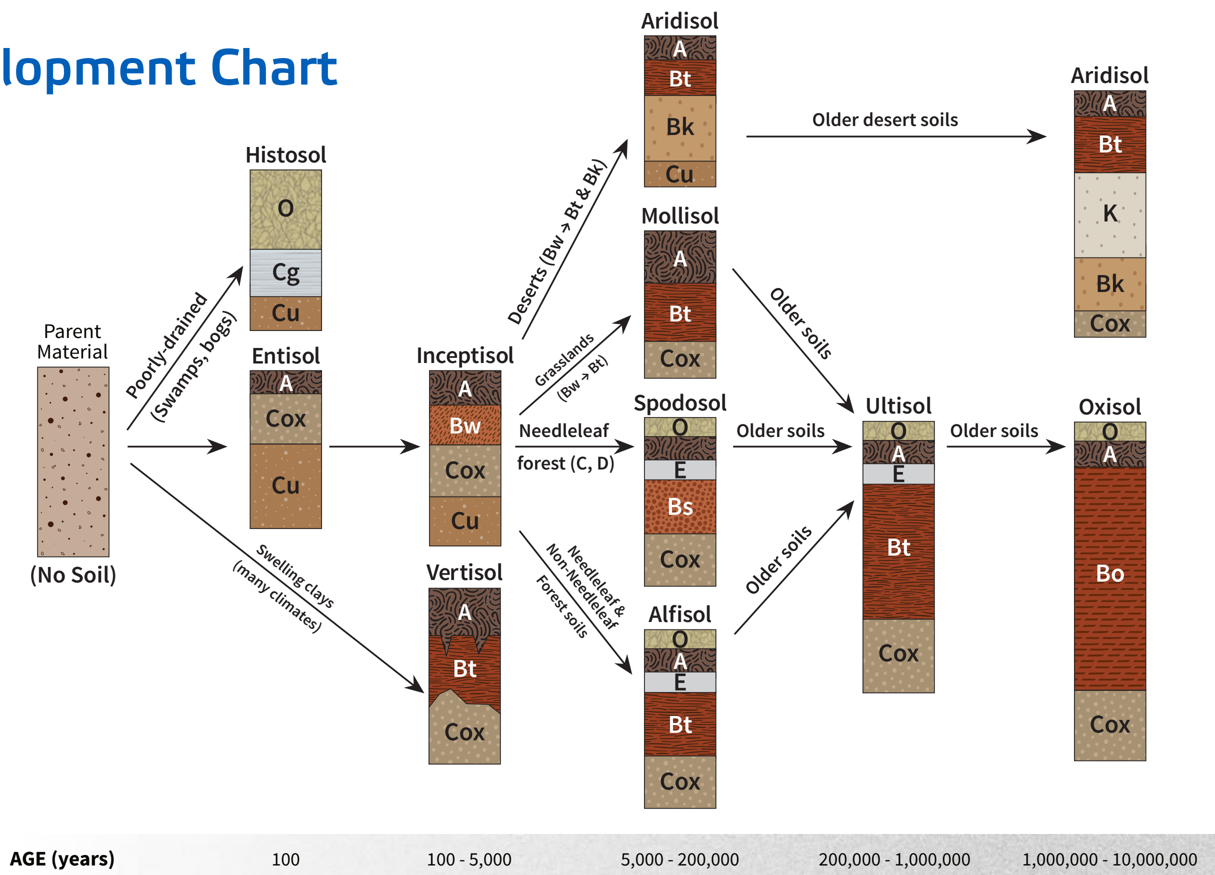


Figure 10 / Soil orders and horizontal characteristics arranged as a function of development (Birkeland, 1999).

Figure 11 / Soil sensors installed in an inceptisol soil with a Bw horizon typical in a cambic epipedon. Picture compliments of the USDA NRCS SNOTEL Program.

1.5 / Soil pH

Soil pH defines the relative acidity or alkalinity of the soil solution. The pH scale in natural systems ranges from 0 to 14. A pH value of 7.0 is neutral. Values below 7.0 are acid and those above 7.0 are alkaline, or basic. Many agricultural soils have a soil pH between 5.5 and 6.5.

While measured soil water content is less directly influenced by pH than other soil parameters, such as bulk density or clay content, the pH of the water in the soil drives many biological and chemical reactions. Soil pH is important to the microbial community, fertilization, and drives the solubility of many organic and inorganic actors influencing many aspects of the soil.

Soil pH is a measurement of hydrogen ion [H+] activity, or effective concentration, in a soil/ water solution. Soil pH is expressed in logarithmic terms, which means that each unit change in soil pH amounts to a tenfold change in acidity or alkalinity. For example, a soil with a pH of 6.0 has 10 times as much active H+ as one with a pH of 7.0. The activity of the hydrogen ion in solution is approximately equal and assumed to be the same as the concentration of hydrogen ion. The word "activity" in this means power in this context. For example if the temperature were to increase, the activity increases and the [H+] becomes more reactive and can be just as reactive toward [OH-] in solution than a higher concentration of hydrogen ion at a lower temperature.

Solutions over a pH of 7 are alkaline and have more [OH-] than [H+]. These conditions are called "basic". An alkaline soil is said to have a high base saturation which can be measured by titration.

The hydrogen ion [H+] and the alkaline counterpart [OH-] primarily exists in the water phase of the soil matrix. If the soil is completely dry the pH is not measurable directly but will still have an acidity or an alkalinity. The difference between pH and the acidity is that pH is a measure of [H+] in solution and the acidity is the overall quantity of [H+] held in soil or readily available from a deprotonation reaction of a conjugate base. The word "deprotonation" means an acid neutralized by alkalinity. While the pH can be measured to obtain the quantity of [H+] and [OH-], there may still be [H+] and [OH-] in the soil that are not in solution and not contributing to the measured pH, but are apart of the acicity and alkaninity. Buffering is the potential ionization of water or the shift in carbonate chemistry that affects the ability of the solution to change the pH. Acidity is the sum of the [H+] (determined by measuring the pH) in solution and the [H+] that could become available to go into solution, upon the addition of a base.

The alkalinity and acidity of the soil is in part influenced by the presence of sodium but is mainly driven by the biology, which in turn drives the carbonate chemistry in solution. The [H+] responsible for acidity and [OH-] reasonable for the alkalinity are at the expense of one another. This means that when acidity goes up, the alkalinity goes down and vice versa. Additionally, the amount of [OH-] in solution can be determined from a simple calculation from pH and the equilibrium constant of water.

$$H_2O \leftrightarrow H^+ + OH^- \quad [1.1]$$

$$pH = -Log\,[H^+] \quad [1.2]$$

As bacteria consume and breakdown dead plant material and organic matter, CO_2 is released, and the CO_2 will dissolve in the water. Once the CO_2 is dissolved in the water, organic acids forms. Because CO_2 is so abundant and has a water solubility, most natural waters are slightly acidic.

$$CO_2\,(g) + H_2O \leftrightarrow CO_2\,(aq) + H_2O \quad [1.3]$$

$$CO_2(aq) + H_2O \leftrightarrow H_2CO_3 \quad [1.4]$$

$$H_2CO_3 \leftrightarrow HCO_3^- + H^+ \quad [1.5]$$

$$HCO_3^- \leftrightarrow CO_3^{2-} + H^+ \quad [1.6]$$

Both [H_2CO_3] and [HCO_3-] can provide [H+] to the solution creating an acidity with lower pH values but if the equilibrium shifts, both [HCO_3-] and [CO_3^{2-}] can adsorb [H+] buffering the solution. In an alkaline soil [OH-] dominates, giving a pH greater than 7 and reducing the concentration of [H+] and shifting the carbonate chemistry to generate [HCO_3-] and [CO_3^{2-}].

The pH of a soil horizon can be influenced by the parent material from which the soil was formed, the chemical nature of the rain or other water entering the soil, land management practices, and the activities of organisms (plants, animals, and microorganisms) living in the soil. Soil pH is an indication of the soil's chemistry and fertility. The activity of the chemical substances in the soil affects the pH levels. Different plants grow at different pH values. Farmers sometimes add materials to the soil to change its pH depending on the types of plants they want to grow. The pH of the soil also affects the pH of groundwater or nearby water bodies.

The pH can also drive the availability of fertilizers. If nitrate is applied to the soil, the nitrate can get all consumed shifting the pH lower which in turn shifts the nitrate back to ammonium ion.

$$NH_4^+ + O_2 \leftrightarrow NO_3^- + 2H^+ + H_2O \quad [1.7]$$

Adding lime or a calcium carbonate to the soil will help adsorb the excess [H+] increasing the availability of the [$NO3^-$] (McBride, 1994).

$$CaCO_3 + 2H^+ \rightarrow Ca^{2+} + CO_2\uparrow + H_2O \quad [1.8]$$

The most accurate way to measure pH is take one-part soil and one-part distilled deionized water and measuring the pH or the water portion with a calibrated pH meter. There are field titration test kits available that can help determine the base alkalinity of the soil. With these kits, a color changing indicator can be added and known amounts of an acid solution can be added to the soil until the indicator changes color. pH litmus paper for measuring the pH of a soil water slurry in the field is also helpful.

1.6 / Soil Bulk Density

The greater the soil density, the less water it will hold, and the slower water will move through it at moisture conditions near or above field capacity. There will often be soil horizons that will be denser than others, giving the soil different hydrological properties with depth. Occasionally, water will stop or slow down and rest on a dense, less permeable layer of soil. This phenomenon is called perched water. If two soil sensors 20 cm apart have very different soil moisture readings, chances are that one of the probes is residing in perched water.

$$\rho_b = m/V \qquad [1.9]$$

$$\phi = 1 - \frac{\rho_b}{\rho_p} \qquad [1.10]$$

The bulk density is associated with the density of a soil ped or a soil matrix. The particle density is the density of an individual soil particle, such as a grain of sand. The two densities should not be confused with one another. The dry bulk density is the dry mass divided by the volume. The porosity, or percent void space of dry soil, φ, can be calculated from the bulk density and the particle density (Shukla, 2014). In many soils, the particle density ρ_p can be approximated using the value 2.65 g/cm^3 to estimate the porosity. It is recommended to measure the bulk densities of the identified horizons in the soil profile where soil sensors are being deployed.

In some soils, there can be a relationship between soil bulk density and the complex dielectric permittivity, particularly the imaginary permittivity. As the densities of soils increase, the molecular relaxation and electrical conductivity components of the soil may increase within the measurement region of the soil sensor (Heil, 2017). This causes the imaginary dielectric permittivity of dry soils to be a function of both the bulk and particle densities, the soil density often creates the need for soil-specific calibrations with some soil sensors in some soils. For soil sensors that isolate the real dielectric such as the Stevens HydraProbe, the effect of bulk density on the soil moisture calibration (Leao, 2010) is minimal based on several studies.

The bulk density however does greatly influence water movement and water storage. In order to have representative soil moisture data, it is best if the soil probe is installed in undisturbed soil.

1.7 / Shrink/Swell Clays

Shrink/swell clays belong to the soil taxonomic order Vertisol and are composed of smectite clays. These clays have a large ion exchange capacity and will shrink and swell seasonally with water content. The seasonal expansion and contraction homogenizes the top soil and the subsoil. As the clay shrinks during a drying period, the soil will crack open and form large crevasses or fissures. If a fissure forms in the measurement volume of a soil sensor, the probe will signal the average of the fissure and potentially generate biased results. If a dry shrink/swell clay is wetted back up, the swelling is immediate. But if a large fissure persists, the fissure may fills with water. If this occurs, the soil moisture measurement will be high, and if the fissure is dry the soil moisture measurement will be lower than expected. If the sensor measurements are being affected by shrink/swell clays, it is recommended to relocate the probe to an adjacent location.

1.8 / Soil Ped Structure and Ped Wetting

A soil ped is a single unit of soil structure. Ped shapes include granular, platy, blocky, and prismatic. Ped sizes can range from 1 mm granules to 10 cm prisms. The preferential pathway water travels through soil is between the peds. This is evident by clay film coatings that develop around a ped. The clay film precursors become dissolved in the pore water. As the pore water subsides the clay film precursors fall out of solution and adhere to the surface of the peds creating the clay film in a process call translocation. The clay film will often delay the infiltration of water into the ped. Thus as the wetting front moves down into the soil, the regions between the peds will be the preferential water pathway. As the wetting front moves through the soil column the soil moisture measurements from a sensor may be temporarily biased by the peds. For example, if the soil probe's measurement volume is residing entirely in a single ped, the probe would not detect the wetting front until the water infiltrates the ped. Likewise, if the sensing volume is residing between several peds, the soil moisture measurements will reflect the movement of water between the peds. During installation, if a horizon has thick clay films around the peds, you may want to use daily averages of soil moisture reading to accommodate soil moisture variations in the peds (Brady, 1974).

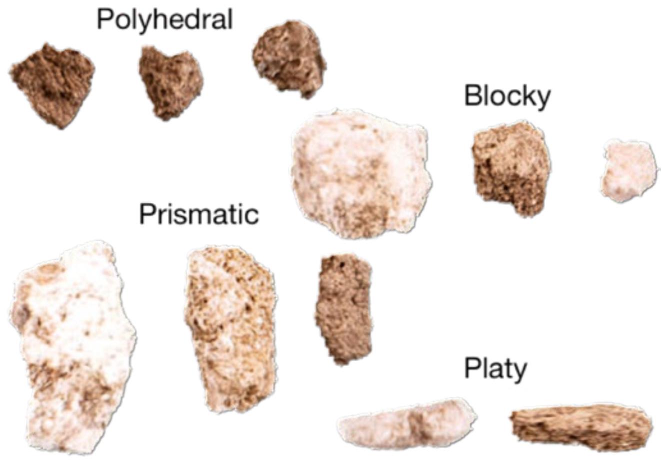


Figure 12 / Soil unit structural peds.

CONCLUSION

Movement of water through soil is complex and the soil properties (pedology) play a major role.

For example, a sand layer common in aridisols and at the surface will drain water very quickly. However, a sand layer under a silt layer in a cambic epipedon will not drain the silt layer until the silt get wet enough to drain downward by gravity. These hydrological phenomenon are captured in the data collected with soil moistute sensors and explained through the data on the soil properties.

When installing meteorological station with soil sensors, knowledge of the local pedology along with a Munsell color book will provide insight into the overall deployment strategy which includes; vertical and horizontal placement of soil sensors, locations of metrological stations, and data assessments.

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REAL PERMITTIVITY	IMAGINARY PERMITTIVITY	PORE WATER EC

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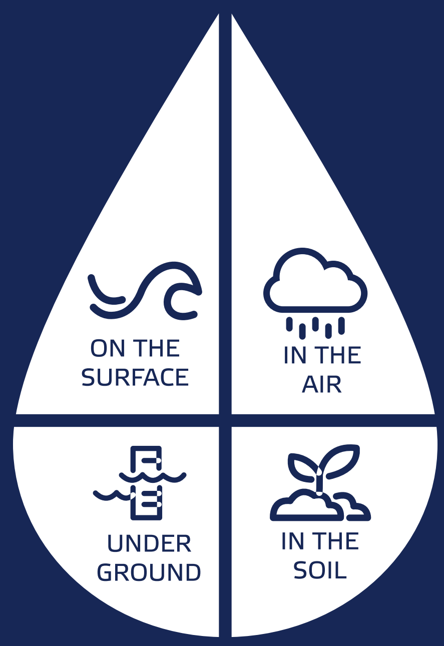

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